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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

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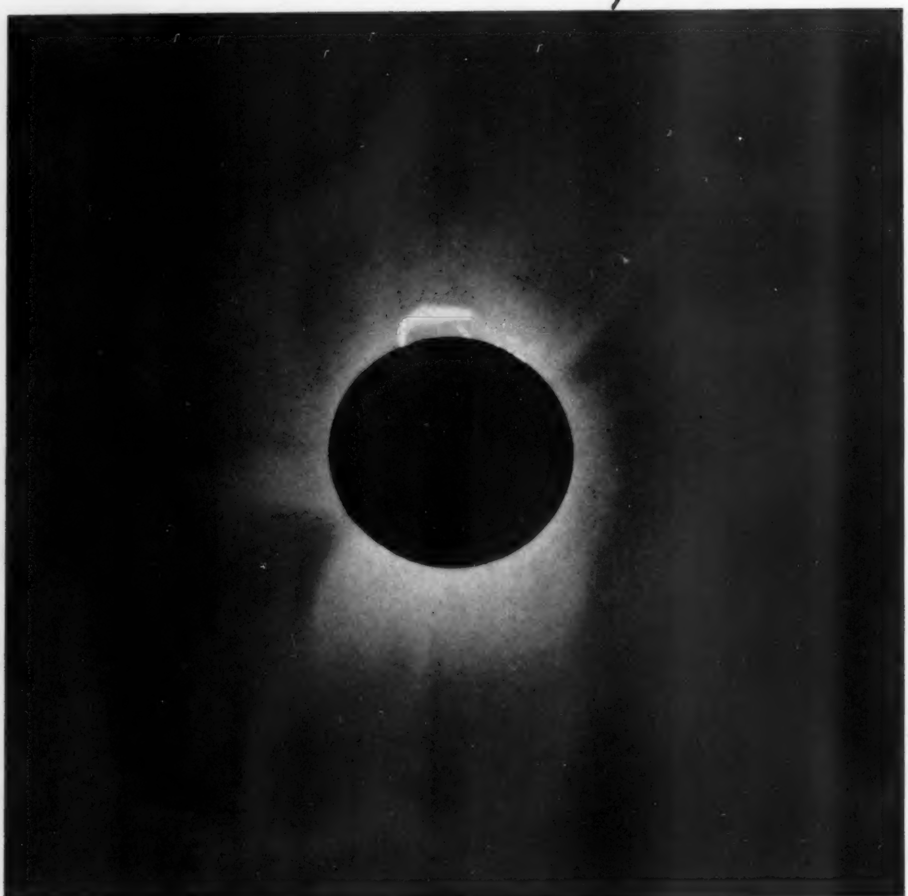

Total Eclipse of May 29, 1919

As photographed at La Paz, Bolivia, by expedition from Smithsonian Observatory

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OBSERVATIONS OF THE TOTAL SOLAR ECLIPSE OF MAY 29, 1919

By C. G. ABBOT and A. F. MOORE

ABSTRACT

Solar corona, during the eclipse of May 29, 1919.—The expedition from the Smithsonian Institution, stationed at El Alto, Bolivia, obtained two very good photographs of the corona, showing many narrow streamers extending nearly two diameters in almost every direction, and a great sickle-shaped *prominence* (see Plate I). The corona was of a type intermediate between that of a sun-spot maximum and that of a sun-spot minimum. A brief account of the expedition is given.

The Smithsonian Institution expedition to observe the eclipse consisted of C. G. Abbot and A. F. Moore. Abbot photographed the corona with twin telescopes of 7.6 cm (3 in.) aperture and 335 cm (11 ft.) focus, and Moore carried on pyranometer observations during the eclipse, as well as at the same time on the day preceding, and at intervals during the night preceding. The present note relates only to the photographic observations, and is mainly for the purpose of reproducing in the *Astrophysical Journal* the coronal photograph which was secured. The full publication of the work will be made in the *Smithsonian Miscellaneous Collections*.

The station was located at El Alto, Bolivia, on the rim of the canyon in which La Paz is situated. The approximate location of

El Alto is: latitude, 16°30′ S.; longitude, 4^h33^m W.; altitude, 4120 meters. Although at a high altitude the sky is rarely free from clouds, but very favorable conditions existed during the total and partial phases of the eclipse.

PHOTOGRAPHIC OBSERVATIONS

Owing to the shortness of the time available for preparation after the expected arrival of the party at La Paz, every possible arrangement had been made in advance to set up the photographic apparatus quickly. For this purpose each of the three boxes which contaned the apparatus was designed in form and construction so as to act as a support to some of the photographic outfit when filled with stones and laid upon the floor of any room which might be found available for the observations. Also every detail of the apparatus was carried without any dependence on such lumber or other material as might ordinarily be available. It was very fortunate that this was so, for the expedition was delayed so that the apparatus was only set up two days before the eclipse.

The briefness of the time available for preliminary tests was unfortunate in one respect. Owing to the very low altitude of the sun (only twenty minutes after sunrise) when the eclipse took place, the refraction of the terrestrial atmosphere was continually changing at the time, so that the apparent motion of the sun in the sky was at a variable rate, not agreeing with that which prevailed later in the day. A test of the clock was made on the day preceding the eclipse, but owing to cloudiness it was not possible to follow quite up to the time of the eclipse. Such observations as were made on the preceding day, however, indicated that the clockwork moved a little too slowly and so the rate of the clock was increased about 3 per cent with the expectation of more exactly following the sun at the time of the eclipse. Unfortunately this proved to be too much of a correction so that the clock moved a little too fast during the eclipse, and the images of the moon are not as truly round as they should be.

The two camera telescopes were rigidly fastened together. Exposures were made by the removal of the two pasteboard boxes which covered the ends of the tubes but were separately mounted

on hinged supports independent of the cameras. As the requisite time of exposure was not accurately known, it was arranged to expose one of the telescopes for 1 minute 30 seconds, the other for 2 minutes 45 seconds.

The program was carried through without any accident, and upon developing the two negatives both were found to be very good, but the exposure of 1 minute 30 seconds seemed to show quite as much extension of the corona as that of 2 minutes 45 seconds. As less drift of the clock occurred during the shorter interval than during the longer we give in the accompanying illustration (Plate I) only the result of the shorter exposure.

There were a great number of sharp, relatively narrow coronal streamers extending nearly two diameters in almost every direction from the sun. Decided evidences occur of coronal streamers at the north and south poles similar to those which are found at times of sun-spot minimum. The corona on this occasion was of a type intermediate between that of a sun-spot maximum, equally extensive in all directions, and that of a sun-spot minimum, with relatively short polar streamers and long equatorial extensions. There was also on the following limb of the sun a great sickle-shaped prominence which extended up from the sun to about one-fourth of a radius, then turned sharply around with a very long extension parallel to the sun's surface. Later in the day this prominence was repeatedly photographed with spectroheliographs in the United States, and then extended as a complete arch of very great height and span.

Taking into account the great length and beauty of the coronal streamers, the splendid crimson prominence throwing its glory over all, and the fact that the eclipse was observed so near sunrise from so great an elevation as 14,000 feet, with a snow-covered range of mountains upward of 20,000 feet high as a background for the phenomenon, it seemed to the observers to be the grandest eclipse phenomenon which they had ever seen.

Astrophysical Observatory
Smithsonian Institution
Washington, D.C.
December 1919

BRIGHT NEBULAE AND STAR CLUSTERS IN SAGITTARIUS AND SCUTUM

PHOTOGRAPHED WITH THE 60-INCH REFLECTOR[1]

By JOHN C. DUNCAN

ABSTRACT

Photographs obtained with the 60-inch reflector are reproduced in five plates. They include the following interesting objects:

In Sagittarius: *Nebula N.G.C. 6523 (Messier 8)*;
Star Cluster N.G.C. 6530 (Messier 8);
Globular Star Cluster N.G.C. 6656 (Messier 22).

In Scutum: *Star Cluster and Nebula N.G.C. 6611 (Messier 16)*;
Swan Nebula N.G.C. 6618 (Messier 17).

The author refers to previous observations regarding these objects, calls attention to interesting details and identifies some of the brighter stars. Plate VI is the first large-scale photograph of the Globular Cluster (Messier 22) which has been published. On this plate there are about 75,000 stars, of which Shapley estimates that one-third are cluster stars.

Dark markings are clearly evident in the photographs of the nebulae N.G.C. 6523, 6611, and 6618.

Spectrum of nebula N.G.C. 6611 (Messier 16).—A spectrogram obtained by Slipher shows the nebulium lines weaker than the hydrogen series, and indicates that the nebula has a small radial velocity.

Star Córdoba No. 12431. The right ascension of this star seems to be incorrectly given in the Córdoba Observatory Catalogue.

Long-exposure photographs of nebulae and clusters made with the 60-inch reflector have been confined chiefly to objects north of the equator because of the better seeing at the high altitudes which they attain. It was the writer's privilege, during the summers of 1918 and 1919, to use this instrument on a number of nights, and the opportunity was utilized for photographing some of the more interesting of the objects that lie farther south. The four objects that form the subject of this article lie within a few degrees of each other in the rich region south of the bright star-cloud of Scutum Sobieskii, a region that includes also the Trifid nebula.

The photographs were made at the 25-foot focus of the 60-inch mirror, which was used at its full aperture. The plates were backed with a burnt-sienna mixture to prevent halation.

[1] *Contributions from the Mount Wilson Observatory*, No. 177.

PLATE II

W

E

Messier 8, Consisting of the Nebula N.G.C. 6523 and the Star Cluster N.G.C. 6530

Scale: 1 mm = 16".8 Enlargement 1.64

Plate II.—The chaotic Nebula N.G.C. 6523 and the Star Cluster N.G.C. 6530 (Messier 8), in Sagittarius. Center of plate (1900.0), $\alpha = 17^h 57^m.9$, $\delta = -24°21'$. 1919, June 27. Exposure three hours. Seed 23 plate. Seeing very good. In preparing the positive for reproduction, the brightest part of the nebula was given a longer exposure than the remainder of the plate in order to bring out the detail.

The object known as Messier 8 is a bright open cluster (N.G.C. 6530) combined with a bright nebula (N.G.C. 6523), the combination being visible to the unaided eye as a hazy condensation in the Milky Way, not far from μ Sagittarii. It is a little more than one degree south of the Trifid nebula, which the nebula of Messier 8 much resembles. Messier's description[1] is concerned chiefly with the cluster, his only reference to the nebula being the remark that near the cluster is a bright star (9 Sagittarii) that is "surrounded by a very feeble light"; but modern instruments show that the nebula is one of the brightest and most extraordinary in the sky. Barnard[2] says of it that, "though seldom mentioned, it is far more remarkable than the celebrated Trifid." Sir John Herschel[3] gives a description and an elaborate drawing, and eloquent descriptions are also given in the catalogues of celestial objects of Smyth and Webb. Barnard has described the nebula in considerable detail,[4] and published photographs[5] of it made with the Willard lens. The only large-scale photograph that, to my knowledge, has appeared in any astronomical publication is the fine Crossley photograph[6] made by Keeler in 1899, although excellent plates have been obtained by Ritchey and Pease at Williams Bay, by Lampland at Flagstaff, and doubtless by others. Keeler[7] describes the spectrum as consisting of three bright lines. Lampland[8] has detected in the nebula eighteen variable stars.

The position given by Dreyer for N.G.C. 6523 is that of the brightest part of the nebula, at the left of the center of Plate II.

[1] Quoted by Flammarion, *L'Astronomie*, **32**, 26, 1918.

[2] *Astronomy and Astrophysics*, **13**, 792, 1894.

[3] *Cape Observations*, 1847, p. 116 and Plate I.

[4] *Loc. cit.* and *Astronomische Nachrichten*, **130**, 234, 1892.

[5] *Publications of the Lick Observatory*, **11**, 1913, Plates 51 and 52.

[6] *Ibid.*, **8**, 1908, Plate 56. [7] *Ibid.*, **3**, 205, 1904. [8] *Popular Astronomy*, **26**, 32, 1919.

The center of the bright cluster appears on the right side of the plate, about 10ˢ farther west than Dreyer's position for N.G.C. 6530. Perhaps the most striking feature of the photograph is the dark rift that cleaves the nebula from northwest to southeast, passing between the cluster and the brightest part of the nebula. This rift is not perfectly dark, but contains certain bright filaments that recall the nebula about Merope in the Pleiades. This filamentous structure occurs also on the left side of the plate, east of the bright star 7 Sagittarii. Besides the great rift, there are many smaller, irregular, sharply defined dark markings in all parts of the nebula, resembling the dark regions of the neighboring Milky Way which are interpreted by Barnard as due to obscuring matter. Some of these small dark markings occur in the very brightest part of the nebula; these, however, are not so dark as those in the fainter portions and would not be easily seen in the reproduction had not this part of the plate been given a longer exposure than the remainder in making the positive. Possibly the absorbing material is not perfectly opaque, but allows some light from the brightest nebulosity to pass through. The abrupt edge of the faint nebulosity on the north and south sides of the nebula may perhaps also be due to obscuring masses. The dark spots in Messier 8 suggested to Miss Clerke the name of "Lagoon";[1] but she seems to have found the name unsatisfactory, as it does not appear in the second edition of her book. Professor Ritchey applies the term "chaotic" to nebulae of this class.

Two of the dark spots shown in Plate II are listed in Professor Barnard's "Catalogue of 182 Dark Markings in the Sky."[2] No. 88 of that catalogue is 38 mm from the right edge and 39 mm from the bottom, and No. 89 is 13 mm from the right and 53 mm from the top, near the bright star Córdoba 12446—not very well brought out in the engraving, though easily seen on the original plate. South of the stars Córdoba 12431 and 12437 and extending eastward almost to 12446 is a remarkable irregular bright line of nebulosity which suggests a thin fold turned edgewise to the observer. About 3′ west and 1′ south of Córdoba 12431 is a shorter, brighter line of

[1] *The System of the Stars*, first edition (1890), p. 284.

[2] *Astrophysical Journal*, **49**, 16, 1919.

PLATE III

W

E

THE NEBULA AND STAR CLUSTER N.G.C. 6611 = M 16

Scale: 1 mm = 14.″4   Enlargement 1.85

the same nature. In the upper right corner of the plate, about 7′ south of Córdoba 12446, is a fainter line of the same general appearance. The appearance of slightly brighter nebulosity just below Córdoba 12466 is due to halation.

The positions and magnitudes of bright stars given in the following table were taken from the *Catálogo de 15,975 Estrellas* of the Córdoba Observatory.[1] The right ascension of No. 12431 as given in that catalogue seems to be in error, as the only star comparable with it in brightness appears on the photograph with about 2^s less right ascension. It is stated in the notes at the end of the Córdoba publication that the position of this star rests on a single observation.

Córdoba No.	Name	Visual Mag.	Place, 1900.0 α	Place, 1900.0 δ	Distance in mm from Edge of Plate
12383......	7 Sagittarii	5.9	$17^h56^m43^s.33$	$-24°16'53''.1$	L 4, B 50
12403......	....	9.4	57 37.20	22 12.8	L 47, T 56
12407......	9 Sagittarii	6.0	44.55	21 45.6	L 53, T 57
12411......	....	8.1	49.02	18 52.7	L 57, B 57
12417......	....	9.0	58 7.09	14 46.0	R 48, B 43
12418......	....	9.6	7.42	5 41.3	R 48, B 11
12420......	....	8.2	7.73	11 9.6	R 48, B 30
12430......	....	8.0	17.84	23 22.2	R 40, T 52
12431......	....	9.0	18.17(?)	26 27.3	R 42, T 41
12435......	....	8.4	25.65	9 50.1	R 33, B 25
12437......	....	8.8	27.89	27 2.4	R 31, T 39
12446......	Piazzi 342	8.0	59 2.52	24 12.3	R 3, T 49

The following defects in Plate II might prove deceptive:

Description	Distance in mm from Edge of Plate
Round, like faint star....................................	R 31, B 58
Round, like faint star....................................	R 22, B 64
Irregular, nebulous, 1 mm diameter........................	R 13, B 56

Plate III.—The Nebula and Star Cluster N.G.C. 6611 (Messier 16), in Scutum Sobieskii. Center of plate (1900.0), $\alpha=18^h13^m.1$, $\delta=-13°51'$. 1919, August 25–26. Exposure 205 minutes. Seed 30 plate. Thick sky and poor seeing.

This object was discovered by Messier in 1764.[2] In the catalogues of Herschel, Webb, Smyth, and Dreyer it is described simply

[1] *Resultados del Observatorio Nacional Argentino en Córdoba*, **22**, 1913.

[2] Captain W. H. Smyth, *A Cycle of Celestial Objects*, **2**, 415, 1844.

as a star cluster, no mention being made of the nebula, though Messier says[1] the stars are "mixed with a feeble light." The nebula was detected photographically by Barnard[2] in 1895 and Roberts[3] in 1897. Though Messier seems to have been the only early observer to perceive the nebula visually, it is no more difficult than the nebula in the Pleiades, and I have seen it easily with the 12-inch refractor of the Whitin Observatory.

S. DM.	Visual Mag.	Place, 1855.0		Distance in mm from Edge of Plate
		α	δ	
−13°4914.....	9.5	18h9m49s.1	−13°47′.9	L 10, B 49
15.....	9.2	52.6	35.8	L 13, B 1
17.....	9.5	55.2	39.7	L 14, B 15
−14 4985.....	8.9	10 13.0	−14 7.7	L 31, T 4
86.....	9.1	13.8	2.7	L 33, T 26
−13 4920.....	9.2	14.3	53.3	L 33, T 64
21.....	9.2	17.0	53.2	L 37, T 65
23.....	9.3	19.4	48.2	L 40, B 52
24.....	9.5	20.6	57.5	L 41, T 46
25.....	8.3	22.7	50.7	L 43, B 63
26.....	8.3	23.2	50.8	L 43, B 65
−14 4988.....	8.5	23.4	−14 1.7	L 43, T 28
−13 4927.....	9.2	27.1	−13 48.4	L 48, B 53
30.....	9.1	39.6	52.6	R 41, T 65
31.....	8.2	42.3	35.6	R 36, B 0
32.....	9.0	43.1	51.7	R 37, B 67
−14 4991.....	8.2	45.0	−14 2.6	R 36, T 24
−13 4933.....	9.8	51.8	−13 52.0	R 28, B 67
34.....	9.3	52.2	58.2	R 29, T 43
36.....	9.4	56.7	59.8	R 23, T 35
37.....	9.8	11 6.1	57.9	R 14, T 45

The large gap in the north side of the nebula led Barnard[4] to compare it to the nebula in Orion. The most interesting feature, however, as disclosed by the present photograph, is the system of sharply defined dark markings of which the most conspicuous is on the southeast side, extending inward beyond the center. This marking so resembles the result of irregular flow of developer that, when it appeared on an earlier negative, its reality was questioned until it was fully verified by the present plate. The nebulosity in a thin line lying along the northern rim of the great dark marking is brighter than elsewhere.

[1] C. Flammarion, *L'Astronomie*, **32**, 239, 1918.

[2] *Publications of the Lick Observatory*, **11**, 1913, Plate 57.

[3] *Celestial Photographs*, **2**, 151, 1899. [4] *Astronomische Nachrichten*, **177**, 233, 1908.

PLATE IV

W  E

THE SWAN NEBULA N.G.C. 6618 = M 17

Scale: 1 mm = 19".5 Enlargement 1.4

PLATE V

W

E

Central Part of the Swan Nebula

Scale: 1 mm = 7."2 Enlargement 3.8

Dr. V. M. Slipher, of the Lowell Observatory, has written me that he obtained a spectrogram of this nebula in September, 1919, showing a spectrum "similar to that of the Trifid nebula and the outer parts of the Orion nebula, in that the Nebulium lines N_1 and N_2 are weaker than the Hydrogen series" and that, like the Trifid, the nebula has a small radial velocity.

The magnitudes and positions of bright stars given in the following table were taken from Schönfeld's Southern *Durchmusterung*.

Plates IV and V.—The Swan Nebula, N.G.C. 6618 (Messier 17), in Scutum Sobieskii. Center of Plate IV (1900.0), $\alpha = 18^h 15^m\!.1$, $\delta = -16°14'$. 1919, July 29. Exposure three hours. Seed 23 plate. Seeing fair.

This nebula was discovered by Messier in 1764[1] and attracted considerable attention from observers throughout the last century. Drawings of it were made by Sir John Herschel in 1833[2] and 1837,[3] Lord Rosse in 1854,[4] Lassell in 1862,[5] Trouvelot and Holden in 1875,[6] and a number of others. It was photographed in 1893 by Roberts,[7] using his 20-inch reflector and giving an exposure of two hours, and in 1899 by Keeler[8] with the 36-inch Crossley reflector and an exposure of four hours. Huggins[9] described the spectrum as consisting of a single bright line ($H\beta$ or λ 5007?), together with a faint continuous spectrum when the image of the brightest part of the nebula was thrown upon the slit.

Messier perceived only a "train of light without stars, 5′ or 6′ in extent"[10]—evidently the brightest part shown in the photographs, lying northwest and southeast. Herschel, in his drawing of 1833, shows the bright, curved part extending southward

[1] Smyth, *A Cycle of Celestial Objects*, **2**, 416, 1844.

[2] *Phil. Trans.*, 1833, p. 461 and Plate XII.

[3] *Cape Observations*, 1847, p. 7 and Plate II.

[4] *Observations of Nebulae and Clusters*, p. 151 and Plate VI.

[5] *Memoirs, R.A.S.*, **36**, p. 49 and Plates VII and VIII, 1867.

[6] *American Journal of Science* (3), **11**, 341, 1876.

[7] *Celestial Photographs*, **1**, 101, 1893.

[8] *Publications of the Lick Observatory*, **8**, Plate 58, 1908.

[9] *Phil. Trans.*, **156**, 385, 1866.

[10] Flammarion, *L'Astronomie*, **32**, 241, 1918.

from the west end of Messier's streak and giving the nebula, in Herschel's mind, the appearance of a capital Ω with the right hook exaggerated. This appearance has led to the various names of Omega, Horseshoe, and Swan—the last applying more appropriately than the others, perhaps, to the view obtained with a moderate-sized telescope. Herschel's drawing of 1837 shows a second curve at the other end of Messier's streak, which explains the description "2-hooked" in the N.G.C. This is evidently the brightest part of the diffuse nebulosity shown near the center and eastern edge of Plate IV. Holden, in comparing his own observations with those of other observers, comes to the conclusion that conspicuous motion took place within the nebula between 1833 and 1875; but a comparison of the photographs shows that no

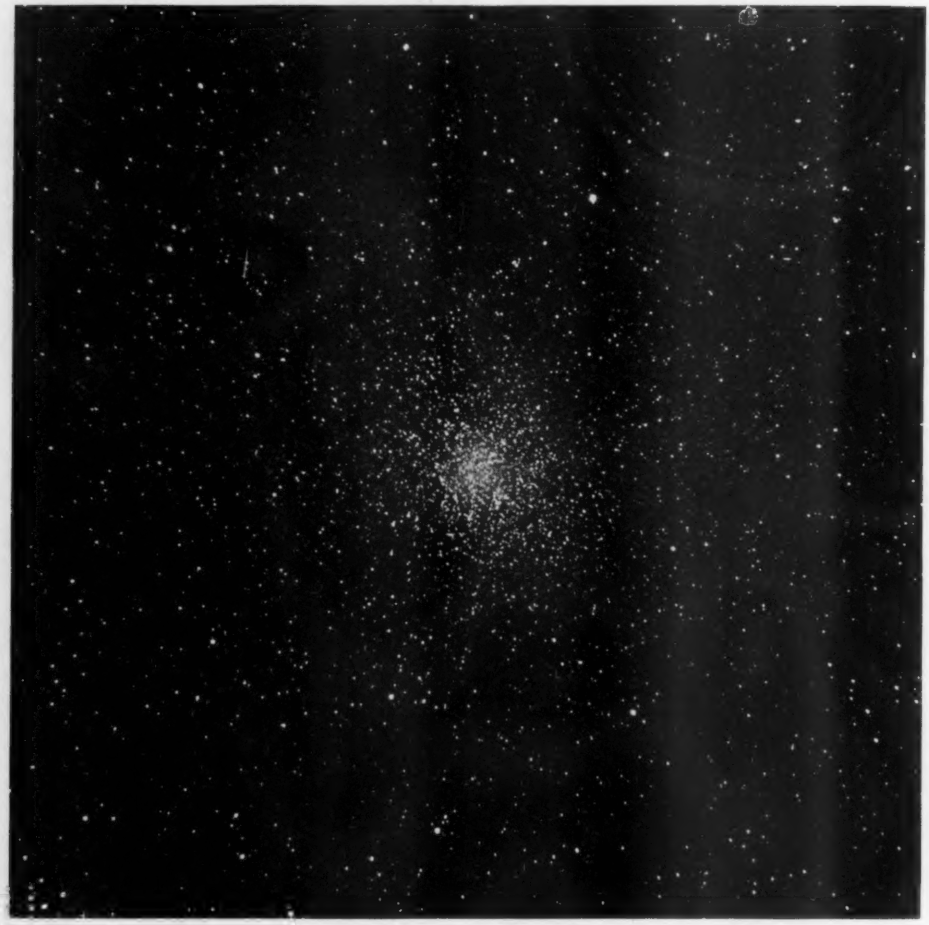
S. DM.	Visual Mag.	Place, 1855.0		Distance in mm from Edge of Plate IV
		α	δ	
−16°4813.....	9.4	18h 11m 47s.6	−16° 4′.3	L 13, B 17
15.....	9.5	12 2.0	0.3	L 22, B 5
16.....	9.6	5.7	15.7	L 26, B 53
17.....	10	9.4	22.6	L 30, T 26
18.....	9.4	13.4	14.2	L 31, B 47
19.....	9.7	22.5	8.6	L 38, B 32
21.....	9.2	25.8	21.0	L 41, T 31
22.....	9.2	26.3	5.6	L 41, B 21
23.....	10	29.4	0.9	L 44, B 6
26.....	9.6	41.8	4.9	L 52, B 19
27.....	9.5	44.5	8.3	L 54, B 29
28.....	9.1	49.5	4.0	R 52, B 17
29.....	8.7	52.2	26.2	R 49, T 16
30.....	8.9	57.7	26.4	R 45, T 16
32.....	9.3	13 5.0	5.0	R 41, B 19
34.....	9.3	8.4	0.6	R 39, B 8
35.....	9.5	12.8	16.3	R 34, B 52
36.....	7.8	26.5	23.0	R 24, T 25

changes on such a large scale occurred between 1893 and 1919, and it seems certain that the apparent changes noted by Holden were due to inaccuracies in drawing.

The photograph brings out much faint nebulosity that cannot be perceived visually, especially to the east and north of the region of Messier. This nebulosity is of a filamentous structure, somewhat remotely resembling that of the Network Nebula in Cygnus, N.G.C. 6992. Like M 8 and M 16, this nebula shows a

PLATE VI

South



THE GLOBULAR STAR CLUSTER N.G.C. 6656 = M 22

Scale: 1 mm = 16."0 Enlargement 1.7

set of dark markings, but they seem of a different kind from those of the former nebulae. The most conspicuous is the square-cornered, sharply outlined space under the neck of the "swan," which is so devoid of light that its contrast with the bright part of the nebula at first gives the impression that it is blacker than the surrounding sky. This dark space is closed on the west by nebulosity which, though faint even on the photograph, was seen and drawn by Lassell. At the north edge of the faint northern extension of the nebula is a dark treelike structure (almost lost in the engraving). Most interesting of all are the dark streaks that cross the region of Messier and especially the head and neck of the swan. They are well shown in Plate V. Some of these seem to radiate from a point near the base of the swan's neck.

The magnitudes and positions of bright stars in the following table were taken from Schönfeld's Southern *Durchmusterung*. The nebula is S. DM.$-16°4820$.

Plate VI.—The Globular Star Cluster N.G.C. 6656 (Messier 22), in Sagittarius. Center of plate (1900.0), $\alpha = 18^h 30^m.3$, $\delta = -23°59'$. 1918, August 6. Exposure three hours. Seed 23 plate. Seeing good. Part of the guiding for this photograph was by Mr. Hoge.

This cluster has been known since the early days of the telescope, and is one of the six "nebulae" in the list drawn up by Halley[1] (the others were the great nebulae of Andromeda and Orion and the star clusters ω Centauri, M 11 and M 13). Smyth says,[2] "Halley ascribes the discovery of this in 1665 to Abraham Ihle, a German; but it has been thought this name should have been Abraham Hill, who was one of the first council of the Royal Society, and was wont to dabble with astronomy. Hevelius, however, appears to have noticed it previous to 1665 so that neither Ihle nor Hill can be supported."

Although one of the most magnificent clusters available to northern observers, appearing larger and brighter than even the great cluster in Hercules, it seems to have attracted comparatively little attention and no large-scale photographs have been published until now.

[1] *Phil. Trans.*, **29**, 390; abridged edition, **4**, 224, 1749.

[2] *Cycle of Celestial Objects*, 1844, p. 422.

Mr. Shapley[1] places the cluster at a distance of 8300 parsecs (or 27,000 light-years) from the sun and 1200 parsecs from the plane of the galaxy—nearer the galactic plane than any other known cluster. Its diameter is at least 30′, so that the light of a star at one end of a diameter must require more than two hundred and forty years to travel to the other end. On the plate reproduced here, Miss Davis has counted about 75,000 stars, of which Shapley estimates that one-third are cluster stars, while the others belong to the Milky Way background. The faintest stars on the original plate are of about the twentieth magnitude, or, on the basis of Shapley's distance, between absolute magnitudes +5 and +6, about like the sun. From counts made on this plate and on others of shorter exposure, Shapley finds that the projection of the major axis of the cluster lies in position angle 25°, and is parallel to the galactic plane.

Two dark spots appear in the reproduction, one 13 mm from the left edge and 32 mm from the top, and the other 57 mm from the left and 34 mm from the top. These are defects due to insensitive spots in the original plate.

The following stars were identified in the Córdoba catalogue referred to in the discussion of Plate II.

Córdoba No.	Visual Mag.	Place, 1900.0		Distance in mm from Edge of Plate
		α	δ	
12919..........	9.0	$18^h30^m35^s.26$	$-24°\ 8'38''.7$	R 44, T 26
12922..........	8.5	18 30 41.49	−23 50 42.0	R 38, B 27

I desire to record here my keen appreciation of the kindness of Mr. Hale and Mr. Adams in giving me a place among the Mount Wilson observers during two summers, and to Mr. Ritchey and Mr. Pease for practical suggestions and for allowing me the use of the 60-inch reflector on certain nights when that privilege would regularly have been theirs.

Whitin Observatory
Wellesley, Mass.
October 1919

[1] *Mt. Wilson Contr.*, No. 160; *Astrophysical Journal*, **50**, 42, 1919.

THE CHARACTERISTICS OF ABSORPTION SPECTRA PRODUCED BY THE ELECTRIC FURNACE[1]

By ARTHUR S. KING

ABSTRACT

Absorption spectra of metallic vapors, produced by the electric furnace.—By placing a short plug of graphite in the middle of a tube furnace, a continuous spectrum corresponding to the temperature of the plug was obtained as a background for a pure absorption spectrum due to the hot metallic vapor. *Barium, calcium, cobalt, iron, nickel,* and *titanium* were investigated.

Relation of Absorptive Power to Temperature Class.—The furnace demonstrates, more clearly than is possible with the arc, the fact that lines of the same intensity in the emission spectrum may differ greatly in absorptive power. This variation was found to be closely related to the behavior of the lines at different furnace temperatures. The lines relatively strong at low temperature are strongest in the absorption spectrum, these lines often being faint in the arc. As the temperature of the plug rises, lines appear in absorption which are given faintly in emission at lower temperature. The result is that the relative intensities in absorption correspond with those in the emission spectrum several hundred degrees lower.

Mixed absorption and emission spectra of metallic vapors.—By placing the graphite plug beyond the middle of the furnace tube, mixed spectra were obtained; for whether the heated vapor emits or absorbs more light of a given wave-length depends on the relative temperatures of the plug and the vapor. Thus the lines of either the low temperature or the higher temperature could be obtained in emission or in absorption or suppressed at will. Striking effects were obtained with *calcium* and *iron*. By adjusting the background, the author secured on the same spectrogram the high-temperature lines in emission, the low-temperature lines in absorption, and intermediate lines suppressed. These experiments may help to *explain stellar spectra containing both bright and dark lines.* Experiments are also described in which the incandescent vapor in the tube, without a plug, gave an absorption spectrum, consisting only of those lines which in the emission spectrum at lower temperature are self-reversed.

Kirchhoff's law; application to the absorption spectra of metallic vapors in the electric furnace. This is briefly discussed.

In former experiments with the electric furnace the writer has occasionally made use of the column of vapor inclosed in a graphite tube to produce absorption spectra, the incandescent background being given by the terminal of a carbon arc burning outside the furnace chamber. In this way the pressure-shifts[2] of absorption lines and the phenomena of anomalous dispersion[3] have been observed.

[1] *Contributions from the Mount Wilson Observatory,* No. 174.

[2] *Mt. Wilson Contr.* No. 60; *Astrophysical Journal,* **35**, 183, 1912.

[3] *Mt. Wilson Contr.* No. 79; *Astrophysical Journal,* **45**, 254, 1917.

In the work here described the furnace was made to supply its own continuous spectrum by placing in the middle of the tube, the heated portion of which was 20 cm long and 12.5 mm internal diameter, a short plug of graphite. The light from the plug passing through a metallic vapor filling the tube produces an absorption spectrum. The arrangement gives a close approach to black-body conditions, and is similar to that of Liveing and Dewar,[1] who studied the reversals of spectrum lines by passing a carbon rod into a carbon tube heated by an external arc.

1. *Relation of emissive and absorptive power.*—It was of special interest to see how the effects obtained may be interpreted as following from Kirchhoff's law, and also how the absorption spectrum compares with the emission spectrum of the furnace at the same temperature, obtained by simply removing the plug, thus leaving all conditions unchanged except the length of the column of vapor.

Kayser, discussing the application of Kirchhoff's law to absorbing vapors,[2] lays stress on the fact that lines in the same spectrum may differ in absorbing power, so that a given relation between the background and the absorbing vapor need not be expected to reverse all of the lines emitted by the latter. If for any given wave-length the emission of the plugged tube, practically that of a black body, be denoted by e, and that of a black body having the same temperature as the vapor in the tube by e', then the emissive power of the vapor will be $e'A$, where A is its absorption coefficient for the given wave-length. The total emission from the tube filled with vapor will then be

$$e+e'A-eA=e-(e-e')A.$$

If an absorption line is to appear, $(e-e')A$ must be above a minimum positive value, the darkness of the line increasing as this product becomes larger. Hence the emission of the vapor for the given wave-length must be less than that of the plug. If $e-e'$ becomes 0, only the continuous spectrum of the plug will appear, a condition frequently obtained in my experiments, usually by

[1] *Proceedings of the Cambridge Philosophical Society*, 4, 256, 1882.

[2] *Handbuch der Spectroscopie*, 2, p. 53.

locating the plug in a cooler portion of the tube and thus reducing the value of e. The vapor may then absorb a given wave-length strongly and still no trace of the line will be seen, the large value of A being rendered ineffective by the zero value of the factor $e-e'$.

Assuming, however, a considerable difference in the emissive powers of the plug and the metallic vapor, the value of A determines whether a line will appear strong in absorption or be invisible as a result of A approaching 0. Kayser notes the well-known difference in reversibility of lines in the arc as evidence that the value of A is not the same for all lines. There is, however, a question as to whether the vapor producing a certain line is present in an appreciable quantity in the outer envelope of the arc, for the method of long and short lines shows that lines difficult to reverse are likely to be confined to the core. The furnace, on the other hand, supplies definite data. A photograph with no plug in the tube shows what lines are being emitted by the vapor. If under these conditions two of the lines are of about the same intensity, and if, when the plug is replaced, one of the lines appears strong in absorption and the other is weak or absent, a real difference in their absorptive powers is evident. Phenomena of this kind have regularly appeared in the absorption spectra to be described. There is a close connection between the absorptive effects and the class of a line as determined by the changes in its intensity at various furnace temperatures, and this relationship has been specially noted.

2. *Probable temperature differences.*—The difference of temperature between the graphite plug and the absorbing vapor is difficult to determine. Pyrometric measurements were made on a thin plug placed at intervals along the tube from near the open end to the middle. Close to the end, where the tube is cooled by the massive contact block, there is evidently a considerable drop in temperature, but for points more than 2.5 cm away from the block the temperature thus measured was surprisingly uniform. For a central temperature of 1800° C. the drop within this limit amounted to about 100°, but at 2400° the difference seemed to be not more than 25°. There is a question, however, as to how fully the inclosed vapor takes up the temperature of the wall of the tube, and as to

the influence, when the tube is very highly heated, of the rapid drop close to the end. There is also the consideration that if the radiation of metallic vapors in the furnace is due to temperature, the emission of a black body should be stronger than that of the vapor at the same temperature. This would give a virtual difference between e and e' at all times when the plug is in the hottest portion of the tube. Evidence in support of this latter point has been given in a previous paper,[1] in which it was noted that the continuous spectrum from a plugged tube extended at least 300 A farther into the ultra-violet than the spectrum of iron vapor when the tube was excited to the same temperature. In any case, the emissive power of the vapor is less than that of the plug and the term $e-e'$ will be greater than 0.

3. *General character of the absorption spectra.*—For the examination of absorption spectra several elements were selected whose emission spectra have previously been studied in detail with regard to temperature variations. These were iron, titanium, nickel, cobalt, calcium, and barium, the first two receiving the larger share of attention. It was evident at once that the absorption spectra differed greatly from those shown at the same temperature in emission. With titanium, no absorption lines showed at 2000°, though a large number of lines, listed in a former paper,[2] appeared at this temperature when there was no plug in the tube. When the temperature of the plugged tube was raised to 2400°, an absorption spectrum was brought out consisting of the same lines as are shown in emission at 2000°. These are the low-temperature lines, belonging to classes I and II, the difference between the classes being in the rate at which the lines strengthen with increasing temperature. Similar results with the other elements showed that the absorption spectrum corresponds with the emission spectrum at a temperature several hundred degrees lower. As a means of picking out low-temperature lines the absorption spectrum, obtained quickly at high temperature, is almost as reliable as the emission spectrum corresponding to the temperature at which the vapor begins to radiate and which often requires a

[1] *Mt. Wilson Contr.* No. 66; *Astrophysical Journal*, **37**, 239, 1913.

[2] *Mt. Wilson Contr.* No. 76; *Astrophysical Journal*, **39**, 139, 1914.

very long exposure to photograph. A different condition prevails in the ultra-violet, however, since in this region the emission spectrum ceases rather abruptly at a certain limit, depending on the temperature, while the easy reversal of ultra-violet lines causes a strong absorption spectrum which extends almost as far as the continuous ground given by the plug.

4. *Relation of absorptive power to temperature class.*—We may now take up the variation of A for different lines and its connection with the temperature classification. The difference in absorptive power of lines belonging to different temperature classes was very distinctly brought out. The strongest absorption lines are those of class I. The stronger lines of class II also show considerable intensity in absorption, but if two lines belonging respectively to classes I and II are of about the same intensity in emission (for example, $\lambda\lambda$ 4415 and 4427 of iron) that of class I will be stronger in absorption. Such lines of class III as appear faintly in emission at low temperatures can be obtained in absorption, but only with difficulty. For instance, in the iron spectrum at 2000°, λ 4260 (class III) is stronger in emission than λ 4258 (class I A), but in absorption, with the tube at the same temperature, λ 4258 becomes the stronger. Numerous other contrasting pairs of the same kind might be noted. The absorption spectrum of iron at 2000° is very similar in the blue and violet to the emission spectrum at 1650°, which is about the lower limit for the appearance of lines of class III. This results simply from the fact that at 1650° the lines of class I dominate the spectrum and, because of their higher absorptive power, they again dominate when a temperature stage is reached at which an absorption spectrum first appears. Lines of classes II and III, which are certainly being emitted by the vapor at this higher temperature, are deficient in absorbing power and either appear faintly or are quenched by the continuous spectrum. The same reasoning explains the absence in absorption, for the temperatures used in these experiments, of lines of classes IV and V and of all but the stronger lines of class III. On account of their relatively small absorbing power, a background of higher temperature would be required to show them in absorption.

It seems unnecessary to list the lines which have thus been obtained in absorption for iron and titanium, since they can at once be selected from the tables[1] of the furnace classification for these spectra. For lines of the same class the relative intensities in absorption are the same as for the furnace in emission, the differences between the two kinds of spectra showing a consistent connection with the class of the lines concerned.

The absorption spectrum of calcium is of interest on account of the variety of types of lines represented. λ 4227 may have great width, depending on the amount of vapor present. H and K are narrow absorption lines, strengthening with the temperature, with little dependence on vapor density. The other calcium lines appearing in absorption within the range λ 3500 to λ 5000 correspond in strength with their furnace classes; the strong lines as usual are of class I, some lines of class II show faintly, while the lines of class III, usually of diffuse structure, are absent. The spectra of the other elements photographed showed a repetition of the conditions noted.

The difference between the arc spectrum and that of the absorption furnace is accentuated by the fact that, in the latter, lines of class I A are very strong and those of class III are weak or absent. In the arc, the reverse condition holds, I A lines being very faint while those of class III are among the strongest. The fact that the strong lines of class III, which fade out at lower temperature, are difficult to produce in absorption is in harmony with the observation of Liveing and Dewar that "it is by no means always the strongest lines which are most easily reversed, but those which are both persistent and strong."

5. *Variation of absorption effects with wave-length.*—The iron spectrum, which was examined in absorption and emission from λ 3000 to λ 8200, furnishes an illustration of the change in the absorption spectrum with wave-length. A plug temperature of 2600° gave no iron lines in absorption beyond λ 5507. Iron lines of class I are few and relatively faint in the red. In the case of other elements, however, there is no difficulty in obtaining lines

[1] King, *Mt. Wilson Contr.* Nos. 66, 76; *Astrophysical Journal*, **37**, 239, 1913; **39**, 139, 1914.

of high absorptive power in this region, the potassium pair $\lambda\lambda$ 7765–99, for example, appearing readily in absorption. In the yellow and green the iron lines of class I absorb strongly, and a few of class II faintly. The strong lines of class III near λ 4900 were absent in absorption, though they appear in emission at much lower temperatures. In the blue, besides a fairly complete spectrum of lines in classes I and II, a few of the strongest lines of class III appeared faintly in absorption. This condition extends into the ultra-violet, where in the emission furnace many lines reverse readily. As would be expected, their strength in absorption corresponds closely with the width of the self-reversal in emission. Presumably higher temperatures would bring out absorption lines of successively higher classes and show lines in the red which appear in emission at low and medium temperatures.

6. *Production of mixed absorption and emission spectra.*—By placing the graphite plug beyond the center of the tube away from the spectrograph, so that some of the metallic vapor is hotter than the plug, it is possible to obtain emission and absorption lines at the same time. The lines then showing in absorption are those of the low-temperature class. When the plug was not quite in the hottest portion of the tube, the pure absorption spectrum was replaced by one in which some of the lines, usually those of class II, appeared in emission on a continuous ground. Moving the plug to a still cooler portion caused a relative strengthening of the emission spectrum, and a position could be found such that the regular emission spectrum appeared complete, with the exception of the most easily absorbed lines of class I, which still appeared in absorption. Owing doubtless to the higher vaporization point of titanium, a mixture with iron showed the iron lines to be more easily absorbed. It is thus simply a matter of adjusting the intensity of the incandescent background to obtain in emission the higher temperature lines (including the enhanced lines when these are given by the furnace) while the low-temperature lines appear in absorption, a difference clearly due to the different absorbing power of lines belonging to different classes.

7. *Effects due to balancing of emission and absorption.*—I have experimented further in this way by placing the plug only 2 or 3 cm

from the farther end of the heated tube, thus causing its emission to be of about the same strength as that of the metallic vapor in the hottest portion. Some lines then appear in emission and others in absorption, according to their temperature class, while others, often among the strongest in the spectrum, are absent, being neutralized by the incipient absorption which they are undergoing. With calcium in the tube under these conditions, H and K appear in emission, and λ 4227 in absorption, with no trace of any other lines from λ 3500 to λ 5000. Some of the high-temperature lines are doubtless quenched by the continuous background on account of their weak emission by the vapor, but many strong low-temperature lines, such as the group of six near λ 4300 and the series triplet λλ 4425–55, disappear because they are beginning to reverse and are in the state where emission and absorption are nearly equal. With iron the effects were very striking. A condition was obtained such that the strongest lines in the blue region, λλ 4271.9, 4308, 4326, 4384, were invisible, while most lines of classes II and III, weaker than these, showed in emission and many of the easily absorbed lines of class I in absorption. The absent line λ 4384 is a member of a triplet of which the lines are always affected alike by changes in the source, but in this case its weaker companions λλ 4404 and 4415 show as emission lines. A change in the position of the plug evidently can be used to eliminate from the spectrum any set of lines having about the same absorbing power. In the case of stellar spectra, especially those containing both bright and dark lines, the principle here involved can hardly fail to be active in causing an apparent lack of certain lines whose absence is not easily explained by the temperature conditions of the star in question.

8. *Production of absorption spectra without the use of a plug.*—In connection with the results obtained with the plugged tube, a class of furnace spectra may be considered, numerous examples of which have been accumulated but which have been of no use in the regular comparison of spectra produced at various temperatures. These spectra appear when the temperature used is so high that the tube filled with vapor (without any plug) gives a strong continuous spectrum. This occurs with some vapors more

strongly than with others and is doubtless due in large measure to the long column of mixed metallic and carbon vapor, although probably the vapor particles reflecting light from the wall of the tube also contribute. The intensity of the continuous spectrum can be increased by operating the furnace at atmospheric pressure, but with high temperature it appears at the usual working pressure of a few millimeters, so that the well-known effect of high pressure in producing a continuous spectrum cannot be operative here. The presence of such a spectrum prevents any comparison of line-intensities with those corresponding to lower temperatures, for which the continuous background is less in evidence. For usable spectrograms, the continuous spectrum must be kept down, so that no faint lines may be quenched by it, and so that when lines reverse we have the normal self-reversal. Any increase in temperature which is accompanied by strong continuous emission brings about a radical change and a more or less complete transition to the absorption spectrum obtained with a plug at the center of the tube. The absorption lines are those of the low-temperature emission spectrum, and, at the highest stage used for temperature comparisons, are for the most part self-reversed. The lines of higher classes and low absorbing power are blotted out by the continuous ground. The result is that at a very high temperature only low-temperature lines are visible, though at a lower stage, before the continuous emission sets in, a spectrum of richness comparable with the arc is seen. The transition between the two is equivalent to an obliteration of the whole emission spectrum; what were formerly the centers of reversals then remain as absorption lines.

SUMMARY

1. By using a furnace tube obstructed by a graphite plug in its hottest portion, pure absorption spectra have been obtained.

2. The types of lines which in an absorption spectrum under given conditions may be expected to be the strongest have been identified. They are not necessarily those which are strongest in the emission spectrum. Instead, the selection is determined by the temperature class, low-temperature lines being most strongly absorbed, with successively higher classes appearing in absorption

as the temperature of the source of the continuous background rises. As a result, the absorption at each stage of temperature corresponds closely with the emission spectrum several hundred degrees lower.

3. Lines of the same temperature class follow the recognized rule for reversed lines, the lines of shorter wave-length appearing more readily in absorption.

4. When the plug is in a cooler portion of the tube, the spectrum consists of both bright and dark lines according to their temperature class; strong lines are then often neutralized through a balancing of emission and absorption.

5. Absorption spectra similar to those given by a plugged tube may be produced without a plug if the furnace contains vapor at very high temperature. The lines then showing are of the low-temperature classes, whose absorptive power is high, while those of smaller absorptive power are obliterated.

6. The phenomena studied in these experiments are those likely to appear when an extended mass of vapor containing temperature gradients is under examination. It is believed that their main characteristics may account for many conditions of line-intensity observed for such masses of vapor.

Mount Wilson Observatory
November 1919

REVISION OF THE SERIES IN THE SPECTRUM OF BARIUM

BY F. A. SAUNDERS

ABSTRACT

Barium spectrum; series of triplets and single lines.—The spectrum of barium contains three systems of series, the triplets, the single lines, and the pairs. After making a careful study of all available data, including recent unpublished observations by King, the author has revised and extended the previously recognized series of triplets and single lines and has identified the lines corresponding to one or more terms of each of several other series. Altogether about 135 lines are assigned to one or other of sixteen series, which include six series of triplets, eight series of single lines, and two inter-system combination series. Accurate constants for these series are given. The fundamental and diffuse series of triplets are unusually complex, and these and other series show curious irregularities both in the relative intensities of the terms and in the wave-lengths. No simple formula of the ordinary type will give the frequencies accurately. The paper includes a brief *explanation of the notation* used in designating the different series.

Recent experimental work has led to a considerable extension of our knowledge of the spectrum of barium. A. S. King[1] published some excellent measurements from plates covering the visible and ultra-violet portions of the spectrum, using a vacuum furnace as source. Since then he has extended the range of these photographs into the ultra-red and taken several plates especially to help in working out the series in this spectrum. All these he has generously turned over to me for study, and the results are here given. If they are of value, the credit should be given to Dr. King.

H. M. Randall[2] has made a careful study of the ultra-red, and Meggers[3] and Eder[4] have helped to fill in a gap between the visible and the ultra-red. Mention should also be made of the dissertations of Schmitz,[5] George,[6] Lorenser,[7] and Werner.[8]

[1] *Astrophysical Journal*, **48**, 13, 1918. [2] *Astrophysical Journal*, **42**, 195, 1915.

[3] *Scientific Papers*, No. 312, Bureau of Standards, 1918.

[4] *Wiener Akad.*, **123**, II*a*, December 1914.

[5] *Zeitschrift für wissenschaftliche Photographie*, **11**, 209, 1912.

[6] *Ibid.*, **12**, 237, 1913. [7] Tübingen, 1913.

[8] *Annalen der Physik*, **44**, 289, 1914.

All these new observations have helped to fix the system of series in this spectrum with more certainty, and the present paper contains an accurate set of constants connected therewith, as well as several new series. A similar study of the spectra of Ca and of Sr, not yet quite finished, makes it possible to settle the nature of certain series in Ba on account of the close analogy with these spectra. The writer has also derived assistance in this task from some observations by S. Popow, made in the laboratory at Tübingen in the winter of 1913–14, under Paschen's direction, on the Zeeman effect in Ca, Sr, and Ba. These have not yet been published in full, but were used by Popow as the basis of one article.[1]

The full spectrum of Ba consists of three systems of series. Each system contains at least four different types of series, and there are combination series derived from these. The present paper is for the purpose of revising the series in the triplet and single-line systems; the pair system is large and important, but is reserved for a future communication.

The results are given in the form of a set of tables, one for each series, with explanatory notes. The notation used has been explained earlier,[2] and is almost identical with that used by Paschen. A brief explanation is here repeated. The best series formula is probably of the type

$$\frac{1}{\lambda}=\nu=L-\frac{N}{(m+a+R)^2},$$

where N is the so-called series constant, approximately constant for all elements; L is the limit of the particular series in question; m is the variable integer; a is a constant peculiar to this series; R is a "residual," which is itself a function of m and of other constants, which diminishes rapidly toward zero for the outer lines of a series (m large). In Rydberg's formula R is zero; in the formula of Mogendorff it has the value $\frac{b}{m}$; but these simple values are by no means generally applicable.

The fraction $\frac{n}{(m+a+R)^2}$ is called the "term," and is accurately known for any series as soon as the limit is found. The terms are

[1] *Annalen der Physik*, **45**, 147, 1914. [2] *Astrophysical Journal*, **41**, 323, 1915.

represented by the symbols (*mp*), (*ms*), (*md*), and (*mf*) in the four types of series, the principal, sharp, diffuse, and fundamental, in the triplet system; (*mP*), (*mS*), (*mD*), (*mF*), likewise, for the single-line system.

TRIPLET SERIES SYSTEM

"Fundamental," or narrow series of triplets, (1*d*) – (*mf*).—This is now the most accurately measured series in Ba, due to the sharpness of the lines in the vacuum furnace, and the excellent results of King. On this account it is mentioned first. The list here given includes a few very faint lines not given in King's paper, but measured since then from his plates, either by him or by the writer. This series was first suggested some time ago[1] and three of its triplets correctly identified. The course of the rest of the series as then suggested proved, however, to be incorrect and was difficult to settle, chiefly because the second member of the series is abnormally faint. Unwilling as one might well be to admit the possibility of series in which the intensities run abnormally, there is now no doubt that they occur. Lorenser was not deterred by the abnormality referred to, and suggested an arrangement for the series which proves to be much nearer the truth. His second member is, however, wrong.

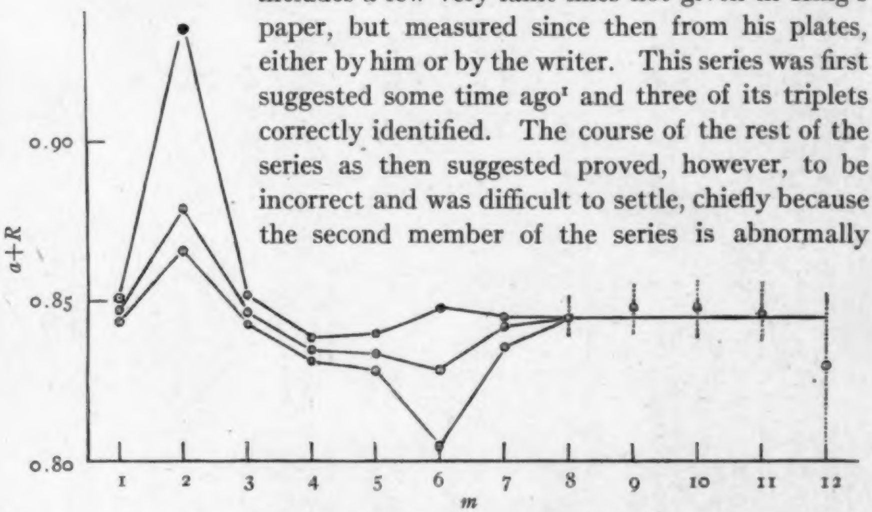


FIG. 1.—Variation of $a+R$ with *m*. Dotted lines show estimated errors

The series is complex, as are the corresponding ones in Ca and Sr, a feature which is, so far, rare in series of this type. It is, moreover, curiously irregular. In order to exhibit this irregularity three curves are given (Fig. 1), showing how the quantity $a+R$

[1] *Astrophysical Journal*, **28**, 228, 1908.

TABLE I

Fundamental Series of Triplets, $(1d)-(mf)$

$$(1d_1)=32433.0$$
$$(1d_2)=32814.1$$
$$(1d_3)=32995.6$$

λ	ν	$\Delta\nu_1$	λ	ν	$\Delta\nu_2$	λ	ν	Terms (mf)	$m+a+R$	m
3997.92	25006.1	381.2	3937.88	25387.3	181.5	3909.92	25568.8	7426.8	3.8438	1
95.66	020.2	381.0	35.72	401.2				7412.8	3.8474	
93.40	034.4							7398.6	3.8511	
3596.33	27798.3	381.2	3547.70	28179.5	181.6	3524.97	28361.1	4634.6	4.8658	2
93.20	822.7	380.9	44.66	203.6				4610.4	4.8786	
79.67	927.7							4505.3	4.9352	
3421.48	29218.9*	381.4	3377.39	29600.3	181.6	3356.80	29781.9	3213.8	5.8432	3
21.01	222.9	381.0	76.98	603.9				3210.1	5.8466	
20.32	228.8							3204.2	5.8520	
			3281.77	30462.8	181.8	3262.30	30644.6†	2351.2	6.8315	4
3323.06	30084.3	381.0	81.50	465.3				48.7	6.8352	
22.80	086.7							46.3	6.8387	
			3222.44	31023.6	181.4	3203.70	31205.0	1790.5	7.8284	5
3262.24	30645.2†	380.8	22.19	026.0†				88.0	7.8339	
61.96	647.8							85.2	7.8401	
			3183.96	31398.6	182.0	3165.60	31580.6	1415.4	8.8049	6
3222.28	31025.1†	381.3	83.16	406.4				07.8	8.8286	
21.63	031.4							01.6	8.8481	
			3155.67	31680.1	181.3	3137.70	31861.4	1134.2	9.836	7
3193.97	31300.2	383.2	55.34	683.4‡				32.8	9.842	
93.91	300.8							32.2	9.845	
3173.72	31499.7†	381.8	3135.72	31881.5	181.9	3117.94	32063.4	932.9	10.845	8
73.69	500.0†									
3158.54	31651.1§	380.5	3121.02	32031.6		‖		781.7	11.848	9
3146.90	31768.3	380.6	3109.63	32148.9				664.7	12.848	10
3137.80	31860.6							572.4	13.846	11
3130.6	31934							499	14.83	12

* Much too strong; perhaps not a member of this series.

† These lines somewhat doubtful, as they are not clearly resolved.

‡ This line may not belong to the series; this triplet irregular.

§ One plate shows a suspicion of a wing on one side of these lines, indicating the presence of an unresolved component, just as one might expect.

‖ There is a faint line at 3103.1, which may belong to the series, but it yields a value of 185 for $\Delta\nu_2$, which is unsatisfactory.

... suspicion of a wing on one side of these lines, indicating the presence of an unresolved component, just as one might expect.
|| There is a faint line at 3103.1, which may belong to the series, but it yields a value of 185 for $\Delta\nu_2$, which is unsatisfactory.

TABLE II

DIFFUSE SERIES OF TRIPLETS, $(1p)-(md)$

$(1p_1)=28514.8$
$(1p_2)=29392.8$
$(1p_3)=29763.3$

λ	ν	$\Delta\nu_1$	λ	ν	$\Delta\nu_2$	λ	ν	Terms (md)	m
25515.7	3918.2	...	...	...	...	...	...	32433.0	1
23255.3	4299.0	877.9	29223.9	3421.1	...	*	...	32814.1	
22313.4	4480.6	878.0	27751.1	3602.6	370.7	30933.8	3231.9	32995.6	
5818.91	17180.7	878.2	5535.93	18058.9	370.6	5425.55	18429.6	11211.6	2
5800.30	235.8	878.1	5519.12	113.9	...	...	...	11279.0	
5777.70	303.2	...	...	...	...	...	...	11333.9	
...	...	...	4332.96	23072.6	370.7	4264.43	23443.3	6244.2	3
4493.66	22247.6	877.8	4323.63	125.4	...	...	...	6267.3	
4489.00	270.6	...	...	...	...	...	...	6320.1	
...	...	...	3947.51	25325.4	370.6	3890.57	25696.0	4041.0	4
4087.31	24459.3†	878.3	3945.61	337.6	...	...	...	4055.4	
4084.87	473.8	...	...	...	...	...	...	4067.5	
...	...	...	3771.93	26504.1	370.6	3719.92‡	26874.7	2843.8	5
3898.58	25643.3	878.2	3769.48	26521.5	...	...	...	2871.4	
3894.34	671.0	...	...	...	...	...	...	2888.7	
...	...	...	3667.93	27255.7	...	§	...	2124.2	6
3789.72	26379.89	878.2	3667.60	27258.1	...	...	...	2134.8	
3788.18	390.6	...	...	...	...	...	...	2137.1	
3721.17	26865.7	878.0	3603.40	27743.7	...	...	...	1646.8	7
3720.85	26868.0	...	...	...	...	...	...	1649.1	

* Measured by Randall. This whole triplet occurs inverted in position. On this account in calculating its "terms" its frequency is to be taken as negative.
† Probably there is a diffuse series line at ν 24459.4 and a sharp series line at ν 24459.1; not resolved.
‡ King's plates show an iron line at 3719.93 from which the Ba line here given cannot be separated, when both are present. In one photograph, when a very small quantity of iron was present, this line showed unusual strength, and was then doubtless largely or entirely due to Ba.
§ King's plates show an iron line at λ 3618.77 which covers the faint Ba line to be expected there, due at 3618.72.

varies with m for each of the three lines, which together constitute the first "line" of each triplet. The curves show that R must be a complex function of m, or else that the true type of formula is quite different from that now accepted. They show, moreover, how curiously the structure of the triplet group opens out and closes again in passing along the series. The accuracy of the constant frequency differences makes it necessary to regard these abnormalities as real. Others of the same sort occur in Ca.

Diffuse or first subordinate series of triplets, $(1p)-(md)$.—The diffuse triplet series has been extended by one term and the accuracy of all wave-lengths greatly improved from King's plates. The limit used here was obtained indirectly, from the fundamental series, for greater accuracy. The curve of residuals for this series, though very far from complete, shows an abnormal course as far as it goes.

Sharp or second subordinate series of triplets, $(1p)-(ms)$.—King's plates show a few new lines of this series. The presence of bands makes it difficult to follow the series farther out.

TABLE III

SHARP SERIES OF TRIPLETS, $(1p)-(ms)$

$(1p_1)=28{,}514.8$
$(1p_2)=29{,}392.8$
$(1p_3)=29{,}763.3$

λ	ν	$\Delta\nu_1$	λ	ν	$\Delta\nu_2$	λ	ν	Terms (ms)	m
7905.80....	12645.5	878.2	7392.44	13523.7	370.6	7195.26	13894.3	15869.3	1
4902.90....	20390.5	878.2	4700.45	21268.7	370.5	4619.98	21639.2	8124.3	2
4239.56....	23580.9	878.4	4087.31	24459.3*	370.4	4026.30	24829.7	4934.0	3
3975.32....	25148.3	878.3	3841.15	26026.6	370.5	3787.23	26397.1	3366.5	4
3828.93....	26110.3	878.2	3704.23	26988.5†	....	....	....	2404.5	5

* See Table II, second note †.

† The last triplet is presented tentatively, as its faintness makes it very difficult to separate from the bands which are present.

Principal series of triplets, $(1s)-(mp)$.—This series is new and very incompletely observed. It is very faint and lies in the ultra-red. It forms combination series (see below) which are analogous to others in Ca and Sr; it is only by means of these that its course can be settled. The first triplet in the table belongs, in a mathematical sense at least, to this series, but is, physically speaking,

the first triplet of the sharp series. The third triplet cannot yet be checked by calculation from any combination and must be regarded as only provisionally located.

TABLE IV

PRINCIPAL SERIES OF TRIPLETS, $(1s)-(mp)$. $(1s)=15869.3$

λ	ν	$\Delta\nu_2$	λ	ν	$\Delta\nu_1$	λ	ν	Terms (mp)	m
7195.26....	13894.3	370.6	7392.44	13523.7	878.2	7905.80	12645.5	28514.8	1
....	....	....	....	....	....	....	....	29392.8	
....	....	....	....	....	....	....	....	29763.3	
....	4582.9 calc.	72.4 calc.	....	4655.3 calc.	171.5 calc.	....	4826.8 calc.	11042.5	2
....	....	....	....	....	....	....	....	11214.0	
....	....	....	21477.2 obs.	4655.1 obs.	171.9 obs.	20712.0 obs.	4827.0 obs.	11286.4	
10326......	9682.4*	49.6	10272.9	9732.0	80.1	10189.1	9812.1	6057.2	3
....	....	....	....	....	....	....	....	6137.3	
....	....	....	....	....	....	....	....	6186.9	

* Recently found by Randall.

SINGLE-LINE SERIES SYSTEM

Principal series of single lines, $(1S)-(mP)$.—This series has proved to be unexpectedly difficult to work out. After the corresponding series in Ca and in Sr were found, it was evident that

TABLE V

PRINCIPAL SERIES OF SINGLE LINES, $(1S)-(mP)$. $(1S)=42029.4$

λ	ν	Terms (mP)	m
5535.53............	18060.2	23969.2	1
3071.59............	32547.2	9482.2	2
2702.65............	36989.9	5039.5	3
2596.68............	38499.5	3529.9	4
2543.2.............	39308	2721	5
2500.2.............	39985*	2044	6
2473.1.............	40423*	1606	7

* Not positively identified as belonging to this series.

this series should occur in Ba also, and should begin with the flame line λ 5535. In an earlier article[1] I remarked that λ 2597 had exactly the right aspect for a member of this series. Later on,[2]

[1] *Astrophysical Journal*, **32**, 155, 1910.

[2] *Physical Review*, **1**, 332, 1913. The series SL2 suggested at that time has proved, in the light of more accurate data, to be incorrect.

I gave the arrangement of the beginning of the series. Recently McLennan and Young,[1] using the method of self-reversal of the lines by the vapor of the metal, which had long been known to be useful in picking out lines of series of this type, have obtained a successful photograph clearly showing the later lines of the series. They also calculated the limit approximately. Their choice of lines for the series differs somewhat from mine. They include, for instance, two lines λ 3275 and λ 2845 for whose existence there is no other evidence. This region has been gone over very carefully by several observers, including King, who uses a furnace as source in which this series must surely appear complete, and in which, in fact, its first line is relatively stronger than usual. High precision is, of course, not claimed for their wave-lengths quoted above, but the known line nearest to λ 2845 is 60 units away, and one must therefore suppose either that there was some error in identification in this case, or else that in a source particularly favorable to this series, and in which some of its lines are enhanced, others fail to appear. The latter assumption seems to me quite untenable.

The course of the series as suggested in the table receives support from the discovery of combination series derived from it, and presented below. The limit of the series has been accurately fixed by means of one of these, $(1S)-(mp_2)$, a combination between this series and the principal series of triplets.

The series is abnormal in the same sense that the fundamental series of triplets is abnormal; that is, the curve of residuals is not a simple one, and no simple formula will fit the series. The outer lines have not yet been measured with satisfactory precision, and therefore the full curve cannot yet be traced.

Diffuse series of single lines, $(1P)-(mD)$.—The experimental evidence necessary for the isolation of the lines of this series is still far from complete. Its limit $(1P)$ is known from the principal series. The first term $(1D)$ is probably 30634.1, a conclusion which is reached by the considerations which follow. There are several pairs of lines in the Ba spectrum with a frequency difference of 11395.3 and one line of each of these belongs to a series

[1] *Proceedings of the Royal Society*, **95**, 277, 1919.

ending at $(1S)$, or 42029.4. This indicates the existence of shifted series, ending at $42029.4-11395.3$, or 30634.1. If this number is then a limit of one or more series, it must itself be a term of some other series. It cannot be a term of the sharp series, for $(2S)$ would be far smaller. The same can be said for the fundamental series. It must therefore belong to the diffuse series and be the term $(1D)$. In this case one of the series ending at this limit is probably the fundamental series, and this is given below.

Having fixed the value of $(1D)$, the difference $(1P)-(1D)$ should give the first line of the diffuse series. $(1P)$ is 23969.2, and therefore the difference is a negative quantity. The occurrence of negative frequencies is not uncommon in series, but has not before been suggested for any diffuse single-line series. It occurs in others, however, e.g., in the diffuse series of pairs and of triplets in the Ba spectrum. Besides, in all sharp series, the first member is also the first member of the principal series, one of these being taken with a negative frequency, thus giving a close relationship in all elements between the series $(1S)-(mP)$ and the series $(1P)-(mS)$. In the spectrum of Ba, and also in Ca and Sr, there exists this same relationship between $(1D)-(mP)$ and $(1P)-(mD)$. The former of these two is the series formerly called SL2, which is given for Ba below, as a combination series of principal type in the single-line system.

The difference $(1P)-(1D)$, ignoring the sign, leads to 6664.9, which hits a line of some strength, observed by Randall in the ultra-red. This is therefore at once the first line of the diffuse series and of the combination series. The term $(2D)$ can be predicted by a formula, but not exactly; it indicates that the next line of the diffuse series is in the ultra-red, but further experiments are needed to settle this line exactly and to fix the others in the series. The rest of the series may, for instance, include $\lambda\lambda$ 9831.7, 6233.59, 5267.03, 4877.69, and 4663.60, and, if so, the combinations $(1p_2)-(2D)$ and $(1S)-(5D)$ appear to exist; but there is no definite evidence on hand on which to decide whether this selection is correct or not. Observations on the Stark effect in Ba should reveal this series, since it appears that diffuse series are as a class sensitive to the effects of electric fields.

Sharp series of single lines, $(1P)-(mS)$.—Both $(1P)$ and $(1S)$ being known, it ought to be possible to guess at $(2S)$ by means of a formula without much ambiguity; but there are many lines in the expected region, the ultra-red, and the true one cannot be settled in this way alone. The term $(2S)$ is, however, very likely to occur in combinations, such as $(1S)-(2S)$, $(2S)-(mP)$, and perhaps others. I have found that if we assume $(2S)$ to have the value of 16400.4, as it well may, according to any reasonable formula, then we get

$(1P)-(2S)=7568.8$ calc.; 7569.8 observed as a strong line by Randall.

$(1S)-(2S)=25629.0$ calc.; 25631.5 observed as a faint line.

$(2S)-(3P)=11360.9$ calc.; 11360.9 observed as medium line.

$(2S)-(4P)=12870.5$ calc.; 12871.8 observed as a weak line.

As these agreements are good, I feel that they are probably correct, and, if so, λ 13207 (ν 7569.8) is the sharp series line in the ultra-red. The next line of this series cannot be picked out with certainty at present. There are several possible lines in the likely region.

Fundamental series of single lines, $(1D)-(mF)$.—As explained above, there are two series ending at the limit $(1D)$, and one of

TABLE VI

FUNDAMENTAL SERIES OF SINGLE LINES, $(1D)-(mF)$. $(1D)=30634.1$

λ	ν	Terms (mF)	m
5826.29	17158.9	13475.2	1
4080.93	24497.4*	6136.7	2
3789.74	26397.7†	4254.4	3

* This line is almost exactly $(1D)-(3p_2)$, but as $(1D)-(2p_2)$ does not occur this must be regarded as an accidental coincidence.

† This line almost coincides with a line of $(1p)-(md)$; it is doubtful which one was measured, or a blend of both.

these is of a new type, which cannot be either principal, diffuse, or sharp. Unless the spectrum contains more than four types, it is safe to call this the fundamental series. In accordance with the constant frequency shifts explained above, there is also the shifted series $(1S)-(mF)$. Lack of proper observations (which are very

difficult to make) prevents us from being quite positive about this series, but the course of it, as far as it is known, is shown in Table VI. This series is probably analogous to those formerly called SL_3 in Ca and Sr.

COMBINATION SERIES IN THE TRIPLET SYSTEM

Series $(1d)-(mp)$.—This combination is strong in Ca and Sr, and its course may be inferred from analogy. In the article by Popow already referred to, one term of the series is given, but in my opinion the identification is incorrect; his arrangement leads to a value of $(2p)$ which is greater than $(1s)$, so that the line $(1s)-(2p)$ should have a negative frequency in Ba. $(1s)-(1p)$ has, of course, a negative frequency, but no series has yet been shown to have two members of this sort, and I am reluctant to admit such a possibility. I have therefore rejected his arrangement.

Since both $(1d)$ and $(2p)$ are each triple, the differences $(1d)-(2p)$ give us nine wave-numbers. Of these, three do not occur as real lines, and one which probably exists as a faint line, bracketed below, is "covered" by a very strong line of another series which occurs quite close to it. This group is arranged according to the Rydberg scheme in the following manner:

Group $(1d)-(2p)$

				21709.0
				72.4
		21600.0	181.4	21781.4
		171.5		
21390.5	381.0	21771.5		[21953]

The identification of this group leads to the value of $(2p)$ and hence to a triplet of the principal series in the ultra-red, given above, of which the third, and faintest, line has not yet been observed. An effort to find the next member of this series, $(1d)-(3p)$, led to the discovery, in a photograph of the vacuum arc, taken by myself, of a very faint pair of lines, the first near λ 3790.27, apparently the strongest of this group. This observation needs to be supported by observations of the other lines of the group.

Series $(2d)-(mf)$.—This series occurs, to the extent of one term only, in the ultra-red of Ca. It probably occurs in Ba also.

The strongest line resulting from this combination is due at ν 3813.0 and Randall has observed a line at 3812.8.

COMBINATION SERIES IN THE SINGLE-LINE SYSTEM

Series $(1D)-(mP)$.—This series is the one which was found in Ca and Sr and then[1] called SL2. It is a shifted series, an exact copy of the principal series, but shifted by a frequency difference of 11395.3 to the new limit, which has been identified above as $(1D)$. An objection may be raised to this series, as the third line of it is fainter than the lines on either side. An abnormality of the same sort, however, occurs in the principal series, and the objection may not therefore be vital.

TABLE VII

SERIES $(1D)-(mP)$

λ	ν	Terms (mP)	m	Shift Number
15000.4............	6664.9	23969.2	1	11395.3
4726.46...........	21151.7	9482.4	2	11395.5
3905.98...........	25594.7	5039.4	3	11395.2
3688.35...........	27104.5	3529.6	4	11395.0

Series $(1S)-(mF)$.—This series is suggested tentatively, but as the three lines in the table give very accurate shift numbers I am disposed to regard it as real.

TABLE VIII

SERIES $(1S)-(mF)$

λ	ν	Terms (mF)	Shift Number	m
3501.12............	28554.3	13475.1	11395.4	1
2785.26............	35893.0	6136.4	11395.6	2
2646.50............	37774.8	4254.6	11395.1	3

Series $(2S)-(mP)$.—This series ought, by analogy with other elements, to occur in Ba. Two members are observed, fairly near their calculated places. The first, and supposedly strongest, member should lie in the ultra-red, and has not been observed; if this line is not found, the existence of the series will become somewhat precarious; but it must be said that all series involving

[1] *Astrophysical Journal*, **32**, 156, 1910.

the terms (mP) show an anomalous lack of intensity for $m = 2$ or 3, and this one may have the same peculiarity.

TABLE IX

SERIES $(2S)-(mP)$

λ	ν	m	Terms (mP)	Shift Number
....	6918.2 calc.	2	[9482]	....
8799.70............	11360.9 calc. 11360.9 obs.	3	5039	25629.0*
7766.80............	12870.5 calc. 12871.8 obs.	4	3528	25627.7

* The calculated shift number is $(1S)-(2S)$, which is 25629.0.

Series $(1P)-(mF)$.—This is probably a very faint series. Only one line has been observed, which is $(1P)-(1F)$; calculated ν 10494.1, observed ν 10493.6 (λ 9527.0). Meggers reports this line as absent from his plates, but an inspection of the plate under the most favorable lighting, for which I was generously given an opportunity, showed the line as present, though faint. The next line of this series should be at ν 17833, but has not been found.

Series $(1S)-(mS)$.—This combination is possible. It gives us ν 25629.0, and there is a faint line observed at λ 3900.37, (ν 25631.5). The agreement is only fair.

INTER-SYSTEM COMBINATION SERIES

Series $(1S)-(mp_2)$.—This series in the spectra of other elements has recently come into considerable prominence. It is strongly enhanced in the low-temperature oven spectra, and occurs in Ca and Sr. Some recent plates taken by Dr. King show that the only line in Ba which has this property and lies in the proper part of the spectrum for the line $(1S)-(1p_2)$ is at λ 7911. The proper region can be found by getting $(1S)$ approximately from the principal series of single lines by calculation, and then subtracting from it the better-known value of $(1p_2)$. In this way the line $(1S)-(1p_2)$ is identified, and from its wave-number and the quantity $(1p_2)$ the value of $(1S)$ is redetermined with greater precision. This series fades away sharply in this group of elements. The second line should be a faint line and its calculated position is λ 3244.20. King's plates show an iron line at 3244.18, and it has not been possible to resolve these two, or to get an

absolutely iron-free spectrum. One of his plates, in which Ba is very rich and Fe faint, shows this line relatively strong, compared with other Fe lines, and its position when measured came out exactly at 3244.20. As the dispersion on this plate is 1.86 A per mm, the error of measurement is considerably less than 0.01 A, so that this line is undoubtedly present. The next line of the series has not been found, on account of faintness.

Series $(1d_2)-(mP)$.—This combination series is fairly strong. Like all the other series involving the terms (mP), this series is somewhat abnormal in the intensities of its lines, the second line being faint. The two closely related series $(1d_1)-(mP)$ and $(1d_3)-(mP)$ might be expected to occur. There are two lines which might possibly be members of the series $(1d_3)-(mP)$, but the agreement is not very good, and there is no other evidence in favor of the existence of these combinations.

TABLE X

SERIES $(1d_2)-(mP)$

λ	ν	Terms (mP)	m	Shift Number
11304.20..........	8844.1	23970.0	1	9216.1*
4284.90..........	23331.2	9482.9	2	9216.0
3599.40..........	27774.9	5039.2	3	9215.2
3413.84..........	29284.3	3529.8	4	9215.2

* The calculated shift number is $(1S)-(1d_2)=9215.3$.

SUMMARY

The spectrum of barium contains three systems of series, the triplets, the single lines, and the pairs. The first two systems are here shown to contain at least four types of series each, together with various combination series. In the triplet system the four type series are not new, but are here extended and revised; two combination series in this system are suggested. In the single-line system, the principal series is revised, and the other three type series in this system are shown in all probability to be present; several combination series in this system occur, including the series formerly called SL2 and SL3; and two inter-system combination series are also found.

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THE SPECTRUM OF ELECTRICALLY EXPLODED WIRES[1]

By J. A. ANDERSON

ABSTRACT

High-temperature absorption spectra, such as those given by the sun and some stars, have not been reproduced fully in the laboratory. The absorption spectra obtained with the arc and the electric furnace have been limited to wave-lengths below $0.56\ \mu$ for iron and have not included the high-temperature lines. The author has developed *a method of obtaining high-temperature absorption spectra*, which consists in electrically exploding a fine wire in a confined space. When the explosion occurs in air confined in a tube or slot, the flash gives a brilliant continuous spectrum crossed by the absorption lines of the elements composing the wire. The spectrograms reproduced show that for *iron* an absorption spectrum was obtained which extends to $0.66\ \mu$ and includes all classes of lines except the pronounced enhanced lines. *Copper*, *nickel*, and *manganin* were also investigated. When the method has been more fully developed it may be possible to imitate stellar absorption spectra of the solar type.

New laboratory source of light.—By discharging a large condenser, charged to 26,000 volts, through a fine wire 5 cm long, about 30 calories of energy were dissipated in about 10^{-5} sec. If all of this energy had gone into the 2 milligrams of wire it would have raised its temperature to about 300,000°. Actually, the brilliant flash which resulted had an intrinsic intensity corresponding to a temperature of about 20,000°, or about one hundred times the intrinsic brilliancy of the sun. The character of the spectrum and also the pressure developed depend, of course, upon the energy per unit mass and also upon the initial pressure and volume of the surrounding gas. When the wire was exploded within a tube or slot under a bell jar exhausted to 2 cm pressure, a line *emission spectrum* was obtained. As the air pressure was raised the continuous background increased in intensity and the spectrum became more and more an *absorption spectrum*. Because of the high temperature, the *continuous spectrum* extends far into the ultra-violet. This source should be useful in studying the *pressure shift* of lines, as pressures of 50 atmospheres can readily be obtained. The spectrograms already secured show the effect clearly. The *appearance* of the flash is shown by direct photographs. Its size corresponds to a speed of propagation in open air of about 3.3 km per second. Some striking *mechanical effects of the explosion* are briefly described.

Meteorites falling into the sun.—In a *theoretical discussion* the author points out that meteorites falling into the sun would be given a relatively enormous amount of energy in a short time and hence would be exploded by mechanical means much as his wires were exploded by electrical means.

Fine wires.—*A simple method of producing on a lathe* wires weighing down to 0.1 mg per cm was developed.

Laboratory investigations deal almost exclusively with emission spectra, that is, spectra consisting of bright lines on a more or less

[1] *Contributions from the Mount Wilson Observatory*, No. 178.

completely dark background. Absorption spectra such as are given by the sun and stars, not being readily produced in the laboratory, must be interpreted in terms of the knowledge derived from a study of emission spectra, which would not be a serious drawback if the mechanism of emission and of absorption were known; since, however, neither is at all well understood, one never feels absolutely sure of his ground in discussing solar or stellar spectra.

Absorption spectra are encountered in the laboratory: (1) in self-reversals of arc or spark lines; (2) by passing white light through cooler vapors or gases. In the arc or spark at atmospheric pressure only a small percentage of the lines are found to be reversed; in the spark at high pressures or in liquids more lines may be reversed, and in the experiments of Hale and Kent[1] at the highest pressure a fair absorption spectrum was produced, though the background was not quite uniform. Possibly at still higher pressures this method would yield a pure absorption spectrum. The high pressure required is, however, a disadvantage in more ways than one.

By passing white light through vapors or gases a pure absorption spectrum is obtained, but, since the hottest source of white light at our disposal is the crater of the arc, it has been found possible to reverse only those lines which are usually found self-reversed in the arc, and naturally very little can be done in the region beyond λ 2500. As an illustration consider the spectrum of iron, perhaps the most important element from the standpoint of the astrophysicist. The low-temperature lines (Groups *a* and *b* of Gale and Adams) are found self-reversed in the arc from the extreme ultraviolet up to about λ 5500, although reversals above λ 4500 are not common. The same lines are also obtained as absorption lines in the electric furnace, either by passing white light from the crater of the arc through the furnace tube or by inserting a graphite plug near the middle of the tube;[2] but no lines beyond λ 5500 have been reversed by this means. Liveing and Dewar mention λ 5615 as having been reversed in one of their experiments, but

[1] *Publications of the Yerkes Observatory*, **3**, Part II.

[2] A. S. King, *Mt. Wilson Contr.* No. 174; *Astrophysical Journal*, **51**, 13, 1920.

this is the only case of reversal for iron in the region less refrangible than λ 5500 that I have come across. The high-temperature lines, and in fact the great majority of iron lines, are nearly unknown as absorption lines except in the sun and stars.

In the course of the experiments described below the absorption spectrum of iron from λ 2250 to λ 6600 has been photographed; all classes of lines except the pronounced enhanced lines are present, as may be seen from the reproductions. Of course only a beginning has been made so far; but the results obtained are quite promising, and it seems reasonable to expect that when the method is fully developed we may be able to imitate successfully the spectra given by the sun and stars. The object of the present communication is to call attention to the method in the hope that other workers may be induced to aid in developing it as rapidly as possible.

It may be of interest to state briefly the idea which led to these experiments: Consider a meteoric particle falling into the sun or a similar center of attraction. Let its mass be m and its velocity v; its kinetic energy is therefore $\frac{1}{2} mv^2$. With the sun as the center of attraction we have $v = 6\times 10^7$ cm/sec., and hence, for $m = 1$ gram, the energy is 1.8×10^{15} ergs or about 4×10^7 calories. How far such a particle would travel before being consumed will of course depend upon the density of the atmosphere through which it moves. In general the path would not be long; hence the time would be short, perhaps a second or, more probably, only a very small fraction thereof. The conditions thus indicate that *a very large quantity of energy is thrown into a small amount of matter in a short space of time.* The effects, spectroscopic and otherwise, of such conditions cannot of course be predicted; hence if any of the circumstances could be produced experimentally they might lead to interesting results.

The conditions to be satisfied are as just stated: to throw a large amount of energy into a small amount of matter in as short a time as possible. By purely mechanical means this does not appear to be easy, but by electrical methods it seemed worth trying.

In the first attempts a small iron wire was inserted in a circuit containing two fair-sized 110-volt direct-current generators in

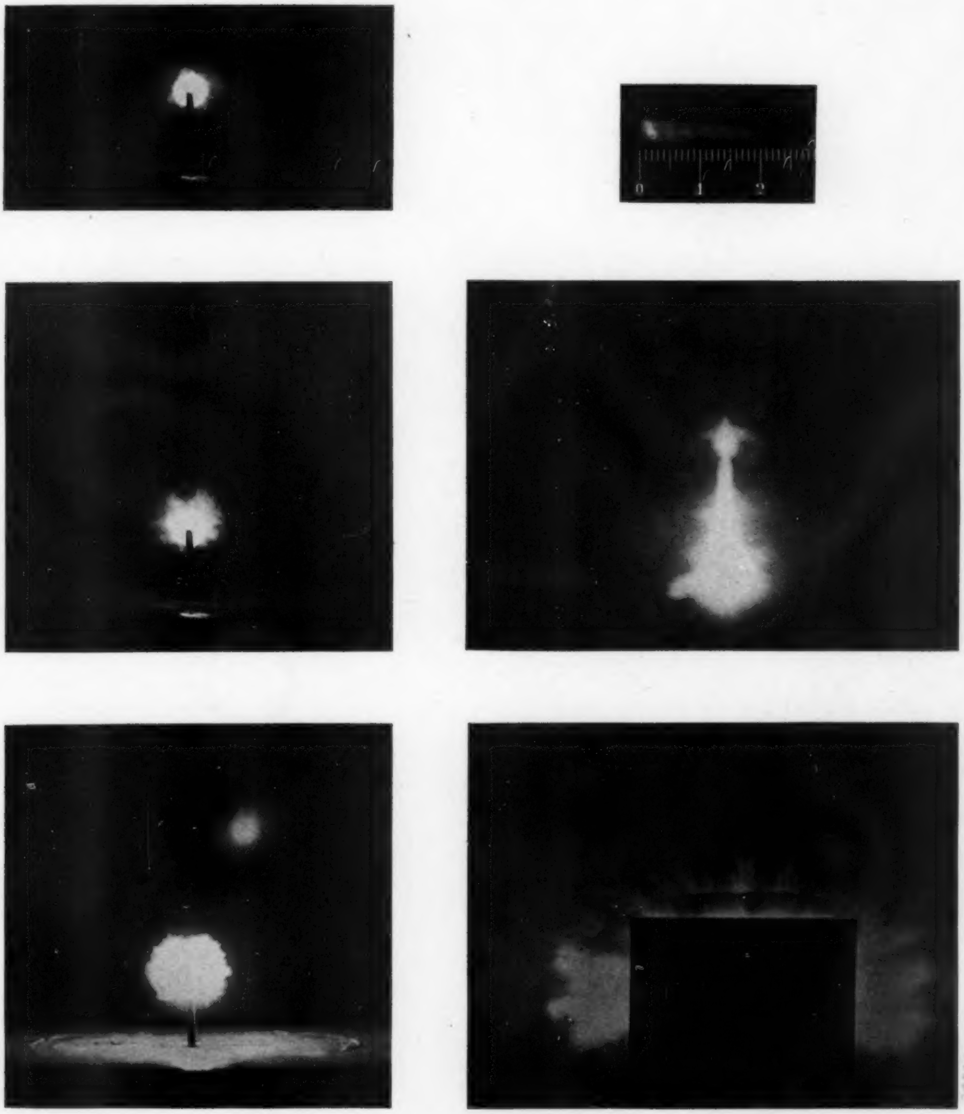
series. On closing the circuit, the wire blew up like an ordinary fuse with a blinding flash of light, the spectrum of which was easily photographed. On account of the large inductance of the circuit containing the armatures of the two generators, the duration of the flash was rather long and the amount of energy developed per gram per second not, therefore, very large. An estimate placed this at about 10^5 calories. A large storage battery would undoubtedly discharge at a much greater rate, but for obvious reasons this was not tried. Instead, a large glass plate condenser was built, which, when charged to about 25,000 volts, contains an amount of energy equal to 30 calories. When discharged through an iron wire 5 cm long and weighing 2 milligrams, this gives very good results. The circuit was so arranged that the frequency of the electrical oscillations as determined by a rotating mirror was 150,000 cycles per second, and the damping large enough to confine most of the energy to the first cycle. (See Plate VII *a*, which is a photograph of the flash as seen in the rotating mirror.) If we assume that the effective time of a discharge is of the order of 10^{-5} seconds and that the larger part of the energy of the condenser charge is expended in the exploding wire, we arrive at a rate of energy development per gram which is of the right order of magnitude. The discharge of this condenser was used throughout the present work.

DETAILS OF APPARATUS AND EXPERIMENTS

The condenser consists of 98 plates of single-strength window glass 40×50 cm (16×20) inches having tin-foil coatings 35×43 cm laid on with shellac. It is charged from a 500-watt, 26,000-volt transformer through a mechanical rectifier, the arrangement of the circuit being as shown in Figure 1. The difference of potential of the condenser plates can be regulated to some extent by varying the length of the series spark-gap *S*. When this is short, 2 mm approximately, and the gap *W* closed by a heavy conductor, sparks pass through *S* at the rate of 2 or 3 per second. When the gap *S* is lengthened to 2 cm, the sparks pass at the rate of one in about 2 seconds. The entire circuit *CSW* is made as short and compact as possible in order to keep the inductance low and the

PLATE VII

d a e b f c



PHOTOGRAPHS OF ELECTRICALLY EXPLODED WIRES

a Explosion photographed by rotating mirror. Numbered divisions of scale correspond to one one-hundred-thousandth of a second

b Explosion in block of wood; end view

c Explosion in block of wood; side view

d Explosion in open air; aperture F/44

e Explosion in open air; aperture F/22

f Explosion in open air; aperture F/5.6. The faint image above is a ghost from the camera objective

frequency high. Since the capacity of the condenser is about 0.4 microfarad, and the frequency 150,000 cycles per second, it follows that the total inductance is only about $\frac{1}{400}$ millihenry. The sparks are very noisy and the observer must not go too close without protecting his ears. This is especially true when a wire is exploded in the circuit. The sound-wave then sent out can be felt as a distinct sharp blow on the face or hands at a distance of 50 cm or more.

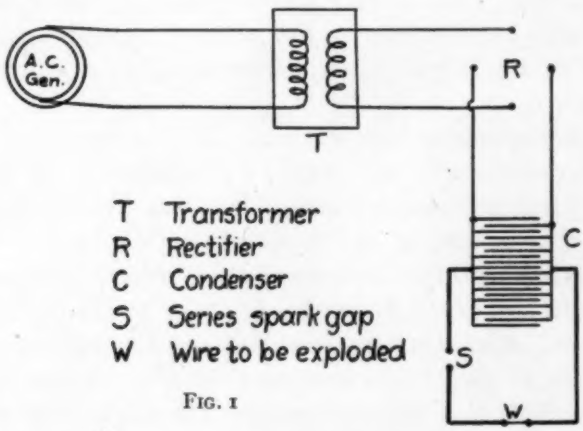


FIG. 1

The mechanical effects of exploding wires are interesting. Some of these have been described by Singer[1] and by F. E. Nipher.[2] If a glass tube with open ends be slipped over the wire the explosion breaks the tube into fragments, which are scattered all over the room; if the ends of the tube are closed by cork stoppers and the tube filled with water, the water disappears completely and the tube is broken into powder so fine that it is sometimes difficult to recognize it as glass. With the wire a few millimeters below the free surface of water in a large glass jar, the sound-wave transmitted through the water by the explosion thoroughly wrecks the containing vessel. The apparent absence of any heat effect is also quite striking. A No. 40 B. and S. gauge (0.080 mm) copper wire with double cotton insulation may be exploded, and in

[1] *Philosophical Magazine*, 46, 161, 1815.

[2] *Experimental Studies in Electricity and Magnetism*. Blakiston, 1914.

most cases the insulation remains nearly unchanged. Tissue paper wrapped tightly around the wire is torn into small bits, but not burned or even charred.

With the present condenser and voltage, it is not possible to obtain good effects with wires larger than No. 36 B. and S. gauge (0.127 mm), or longer than 8 cm; in fact smaller and shorter wires give better results. At first this was a great inconvenience, as it was found impossible to procure such small wires on the Pacific Coast. The difficulty was overcome by one of the mechanicians, who found a neat way of making practically straight lathe turnings of any length, in sizes from less than 0.1 milligram per centimeter up.

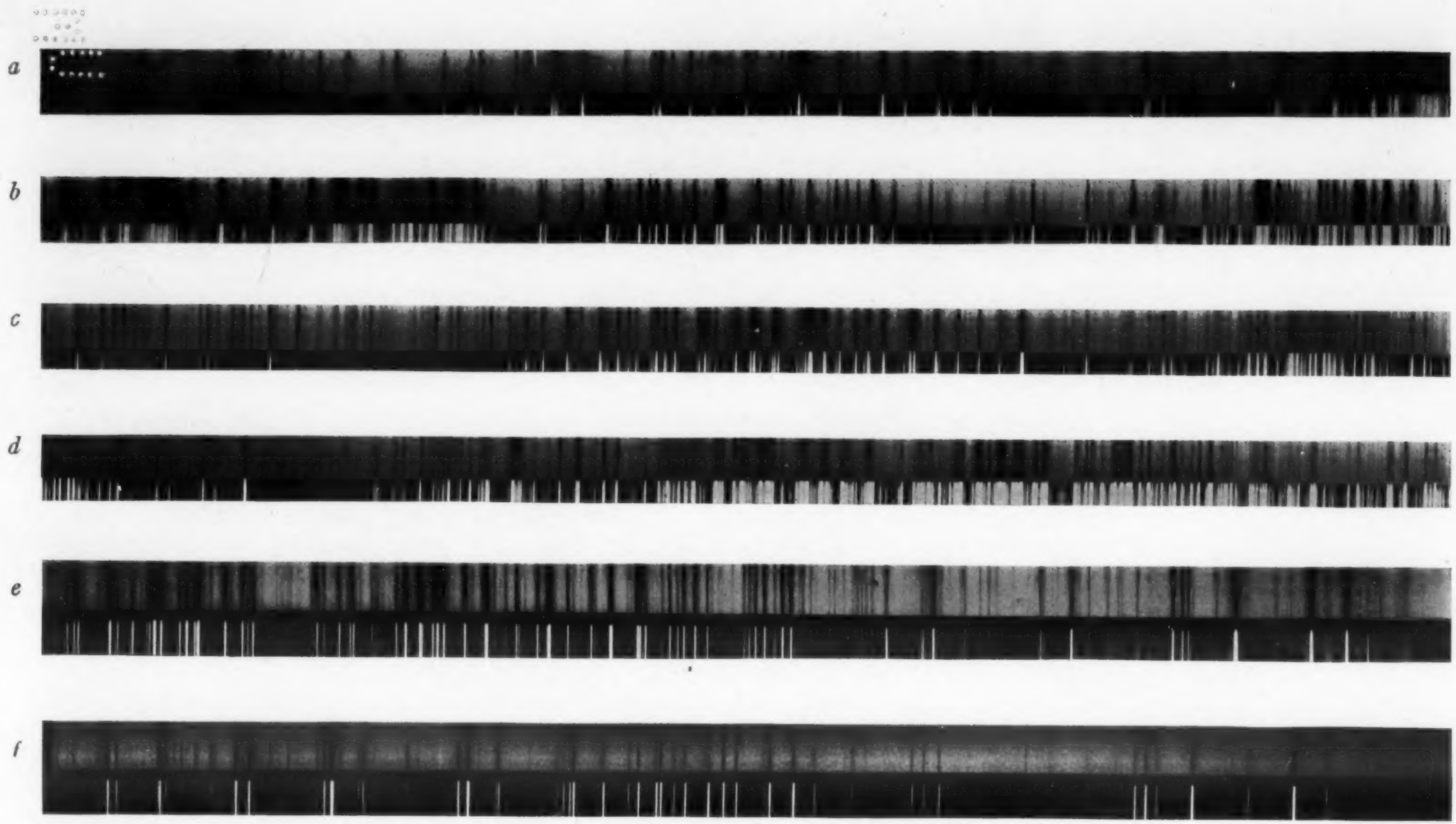
In photographing the spectrum of the explosions a plane grating spectrograph was used. The collimator is a 12.5 cm (5 in.) Brashear telescope lens of 150 cm (60 in.) focus. The grating is a 10 cm (4 in.) Rowland, known as the "Kenwood grating," having bright second and third orders. The camera lens is a Bausch and Lomb Tessar Ic, F/4.5 of 39 cm ($15\frac{3}{4}$ in.) focus. The second-order spectrum was used and the grating so inclined to the axis of the camera lens that the dispersion at the middle of the plate is 6 A per millimeter. The ultra-violet region was photographed with a large Fuess quartz spectrograph, giving a scale at λ 2300 of about 4.5 A per millimeter.

RESULTS

The following are the general conclusions from the work up to the present time:

1. *Wire exploded in the open air.*—When viewed side on, the spectrum consists of bright lines, with faint self-reversals in the green region and more prominent reversals in the violet. There is a continuous background of increasing intensity toward shorter wave-lengths, but not very strong. Viewed end on, the reversals are more prominent throughout and the continuous background very much strengthened. At λ 3700 the strength of the background is so great that this portion of the spectrum looks very much like a normal absorption spectrum. Open-air explosions were not studied in the region beyond λ 3600.

PLATE VIII



SPECTRA OF ELECTRICALLY EXPLODED IRON WIRES WITH IRON ARC COMPARISON

Quartz Spectrograph: *a*, λ 2270 to λ 2490; *b*, λ 2472 to λ 2764; *c*, λ 2780 to λ 3280; *d*, λ 3216 to λ 4075
Grating Spectrograph: *e*, λ 3700 to λ 4090; *f*, λ 5143 to λ 5645

2. *Wire surrounded by a wooden tube 1 cm in diameter and viewed end on.*—At atmospheric pressure the spectrum is perfectly continuous with absorption lines only, from λ 2250 to above λ 5700. To the violet of λ 4500 the lines are in general quite narrow and sharp; to the red of λ 4500 the flame lines are sharp, while lines of groups *d* and *e* are rather wide and diffuse. A spectrogram of the region λ 6100–λ 6600 shows also a continuous spectrum with absorption lines, but there are faint traces of emission lines (enhanced iron lines). Using this arrangement under a bell jar, the region λ 3600–λ 4200 was studied in air at pressures ranging from 2 cm to 20 cm. At 2 cm all lines were bright and very few showed self-reversals, except H and K (these came no doubt from the wood). From 5 cm to 13 cm pressure the continuous background increased rapidly in intensity; reversals became gradually more prominent, and the bright lines broadened and in general shifted toward longer wave-lengths, so that at 10 cm numerous lines showed as a fine absorption line in the normal position with a broad emission line lying wholly on its red side. At 15 cm and 20 cm there was no trace of bright lines, the spectrum being perfectly continuous with the absorption lines in general very fine.

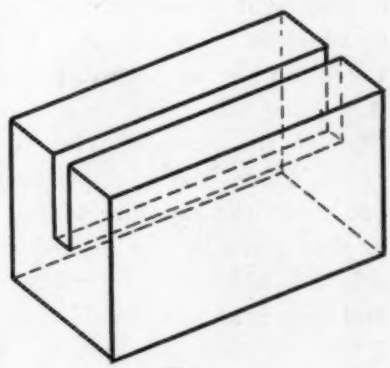


FIG. 2

3. *Wire placed in a cut in a block of wood as indicated in Figure 2.*—The cut mostly used was 4 cm long, 2.5 cm deep, and 3 mm wide. This gives the same spectrum as that produced by the tube just described; it is, however, much easier to load, and is better adapted for projection on the slit of the spectroscope. The spectra reproduced in Plate VIII were taken with this arrangement, viewed end on.

4. *Brightness of the explosion as a source of light.*—Since the spectrum is continuous it becomes possible to compare the brightness of the source with that of the sun, for example, by merely

comparing the exposure-times which give the same density on the photographic plate, using the same spectroscope and projecting apparatus in both cases. The method is simply one of direct substitution. Such a comparison was made in the region λ 3900–λ 4000, using both the quartz and grating spectrographs, and in the region of λ 5500 using the grating instrument. The results are as shown in the accompanying table:

No. of Successive Explosions	Exposure to Sun for Equal Density	Region	Spectrograph
	Sec.		
3	1/200	λ 3900–λ 4000	Quartz
10	1/40	λ 3900–λ 4000	Grating
48	1/10	λ 5200–λ 5600	Grating

It remains to estimate the equivalent duration of an explosion. Plate VII*a* shows that the total duration of light of sufficient intensity to affect the photographic plate exposed with the rotating mirror is not over 1/20,000 sec. It also shows that the greater part of this light is concentrated in the first half-cycle, the duration of which is 1/300,000 sec. Hence if we call the equivalent time 1/100,000 sec. we are overestimating rather than underestimating it. Using this value we find for the ratio of exposure to sun to that of the explosions for the three comparisons given above 167:1, 250:1, 200:1, respectively, or in the mean that it requires 200 times the exposure to the sun to produce the same density as that given by the explosions. The sunlight is of course considerably reduced in intensity in passing through the atmosphere, and there is an additional loss at the speculum mirror which reflects it into the projection system. If we say that only one-half of the light from the sun reached the projection system we still find this new source to be 100 times as bright as the solar surface.

5. *Direct photographs of the explosion.*—Plate VII*b* shows an end view of the explosion in the block of wood, and Plate VII*c* is a side view of the same. The contraction of the luminous column above the slot in the end view is evidently connected with the sharply defined "shadow" above the block in the side view. This apparent shadow is a little surprising and an explanation does not readily suggest itself.

Plate VII*d*, *e*, *f* shows end views of the explosion of a wire in the open air. They were taken with the camera lens stopped to F/44, F/22, and F/5.6, respectively, so as to get the effect of exposures of different "lengths." The F/44 exposure, together with a similar one taken side on (not reproduced), show plainly a central core of luminous vapor, having the form of a solid cylinder 22 mm in diameter and of a length somewhat greater than that of the wire used, the ends of the cylinder being roughly hemispherical caps. The remarkably sharp outer boundary of this cylinder indicates that it marks the limit reached by the expanding gases at the end of the first half-cycle, that is, at the end of 1/300,000 sec. The F/22 exposure shows clearly a fainter second cylinder outside the first, whose diameter is roughly 45 mm. Its outer boundary is, however, rather ragged in this exposure, and even in the F/5.6 exposure it is far from being as sharp as that of the inner cylinder. The outer cylinder probably marks the limit reached by the gases at the end of the first cycle, and its light is chiefly derived from the current during the second half-cycle, the greater part of which must have passed through the inner core.

The vapors undoubtedly go on expanding through the succeeding cycles, but partly on account of their rapid cooling due to expansion, and partly because of the great diminution of the current intensity, the corresponding cylinders fail to be registered on the photographs.

If the explanation just given is correct, we find for the velocity of the expanding gases 3.3 km per second, or about 10 times the velocity of sound in air at normal temperatures.

When the wire is exploded in the slot in the block of wood, the two regions corresponding to the two cylinders can still be seen quite well on the photographs, but they lack the sharp outline shown in the open air, perhaps owing to the resistance to motion offered by the confining walls of wood. It is clear, however, that the velocity in this case is considerably greater, measurements on one of the best plates giving 30 mm and 54 mm respectively, instead of 22 mm and 45 mm for the open air.

6. *Pressure in the gases of the explosion.*—The experiments of Hale and Kent, showing that a spark discharge in gases at a pressure

of 50 atmospheres or more gives a spectrum at least partially continuous, suggested that the cause of the continuous spectrum observed in these experiments may be a very high pressure in the gases formed by the explosion. An effort to estimate the order of magnitude of this pressure was made as follows: A hole 7 mm in diameter was bored through a block of wood weighing 130 grams. The block was then split into two parts by a cut passing through the axis of the hole. One-half was rigidly mounted, and the other suspended as a pendulum so as to hang in contact with the immovable half. The wire was mounted centrally in the hole and the velocity of the movable half produced by the explosion was measured and found to be 135 cm/sec. The mass of the movable block being 65 grams, its momentum was $65\times 135=8775$ gr. cm/sec. The wire in this case was a No. 36 B. and S. gauge (0.127 mm) nickel wire, 6 cm long, 48 mm being inside the opening in the split block. The mass of 48 mm of this wire is 4.8 mg. The momentum is of course equal to the product of the pressure, area, and the time. The pressure varies and is a function of the time. Not knowing the law of variation or the exact value of the time, only very rough estimates of the pressures could be made. The time in this case is of course not the same as the duration of the light, because the emission of light, being largely due to the flow of current through the gases, will cease after a few cycles; the gases, however, go on expanding until atmospheric pressure has been reached. If we assume the equivalent time to be that during which the maximum pressure would produce the momentum observed, we may reasonably suppose that its value would be somewhere between 1/50,000 and 1/10,000 sec., and probably nearer the latter figure. This gives, for the pressure, a value lying between 135 and 27 atmospheres, with the probability in favor of a value of 40 or 50 atmospheres. An independent method of estimating the pressure is as follows: Assume that the nickel wire is transformed into monatomic nickel vapor at a temperature of 20,000° C., which is the order of temperature to be expected from the intensity of the light. The volume at atmospheric pressure would be 136 cu. cm, and if we neglect leakage through the open ends of the tube and merely divide by the volume of the tube, viz., 1.82 cu. cm,

we find 75 atmospheres as an upper limit for the pressure, which is in fair agreement with the estimate from the momentum of the block. We cannot be far from the truth if we say that in this experiment the pressure was of the order of 50 atmospheres.

The iron wires exploded in making the spectrograms accompanying this paper weighed only 0.4 as much as the nickel wire used in the experiment just described, and the volume of the slot in which the wires were placed was 2.5 cu. cm, or 1.4 times as great, so that in this case the pressure could hardly have been more than one-third of that just estimated, or of the order of 20 atmospheres. It seems reasonable to conclude, therefore, that the pressures developed in these explosions are not nearly as high as those which have often been used in spectroscopic investigations, and hence that *very high pressure in a gas is not at all necessary for the production of a continuous spectrum.*

7. *Experiments with other elements.*—A few spectrograms were made using copper, nickel, and manganin wires. With manganin the continuous spectrum has about the same brightness as with iron; with nickel it is brighter; while with copper it is very much fainter.

DISCUSSION

It may not be out of place to return for a moment to the idea which prompted these experiments. As stated above, this was to determine if possible the spectroscopic result of the fall of a meteoric particle of very high velocity into a resisting medium, such as the solar atmosphere. The general effect would be an extremely rapid vaporization of the materials forming the particle. In these experiments we have a rapid vaporization of a metal in the form of a thin wire. The analogy ends here, for in one case the vaporization is produced by mechanical, in the other by electrical, means. That the two methods would yield identical results is not to be expected; but on the other hand it is hard to advance any valid reason why they should be radically different. There is another difference, and an important one, in the amounts of energy available in the two cases. In our experiments the total energy of the condenser charge was 30 calories, and not all of this small amount went into the wire. The same wire falling into the sun

would develop 80,000 calories—in a longer time it is true, yet one cannot help feeling that an adequate imitation of what must happen in the sun requires much more energy than was available in the present work. The following general conclusions seem to be reasonable: A very small particle would be consumed in the extreme outer regions of the sun's atmosphere where the pressure is exceedingly low. The path of the particle would therefore be long and the rate of development of heat energy low. Under such conditions the spectrum would most likely consist of bright lines, with little if any continuous background. Particles large enough to reach a level where the pressure is appreciable would encounter an enormous resistance, and the development of heat energy would be extremely rapid, perhaps hundreds of times as rapid as in the present experiments. Here it seems likely that a continuous spectrum with absorption lines would be produced.

The experiments will be continued with a larger condenser and higher voltage. Attempts will also be made to observe the explosions in gases other than air; hydrogen, for example, should be interesting.

The author desires to express his thanks to Mr. Ellerman for help in some of the photographic work, and for his kindness in preparing the plates for reproduction. The author is also indebted to Mr. Sinclair Smith, who assisted throughout the experimental work.

SUMMARY

1. Fine wires exploded by a condenser discharge give a brilliant continuous spectrum crossed by the absorption lines of the element composing the wire.

2. The continuous spectrum extends into the extreme ultra-violet.

3. The intrinsic brightness of the explosion as a source of light is very high, being apparently much greater than that of the solar surface.

4. The pressure in the gases giving the continuous spectrum is not excessive, being at most of the order of 20 atmospheres.

Mount Wilson Observatory
December 1, 1919

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS[1]

FIFTEENTH PAPER: A PHOTOMETRIC ANALYSIS OF THE GLOBULAR SYSTEM MESSIER 68

By HARLOW SHAPLEY

ABSTRACT

Globular star cluster Messier 68.—The paper contains the results of a characteristic *photometric analysis* of this hitherto unexplored typical cluster, based on fifteen photographs made at the primary focus of the 60-inch reflector. Twenty-eight *variable stars* were discovered, all but one of which appear to be typical, short-period, cluster variables. This cluster is poorer in *giant stars* than some others, as only 250 are brighter than the absolute magnitude zero. The magnitudes and colors of 56 of the brightest of these are tabulated. Most of them are red or yellow. The *distance* of the cluster as computed by three methods which give concordant results is about 55,000 light-years. The *form* is quite accurately circular as far as the two thousand brightest stars are concerned.

Stellar clusters. Further evidence in support of the following general conclusions is supplied by the analysis of M 68: (1) Cluster type *variables* are bluer at maximum than at minimum brightness. (2) Their mean brightness appears to be an astrophysical constant which is a little more than one magnitude fainter than the mean brightness of the 25 brightest stars of the cluster. (3) The fainter the *giant star*, the bluer is its color, on the average. (4) The brightest giant stars are always very red and have absolute photo-visual magnitudes between -4 and -3. (5) The general *luminosity curve* for the stars of the cluster differs widely from a symmetrical probability curve. (6) The *distance* of such clusters can be computed from the diameter of the image of the cluster, or from the mean magnitude of the 25 brightest stars, or from the mean magnitude of the short-period variables.

The present paper reports on a characteristic photometric analysis of a typical globular cluster. The intention of the report, in addition to presenting explicit results that come out of the study of Messier 68, is to examine numerically some of the working hypotheses at the basis of earlier work on clusters,[2] and also to illustrate what astrophysical information can be derived from an inextensive survey of one of the globular systems. There is a considerable number of clusters no fainter than Messier 68 concerning whose structure little is now known.

[1] *Contributions from the Mount Wilson Observatory*, No. 175.

[2] For example, that relating to the general applicability of the adopted methods of determining parallax; cf. Section 5 on page 56.

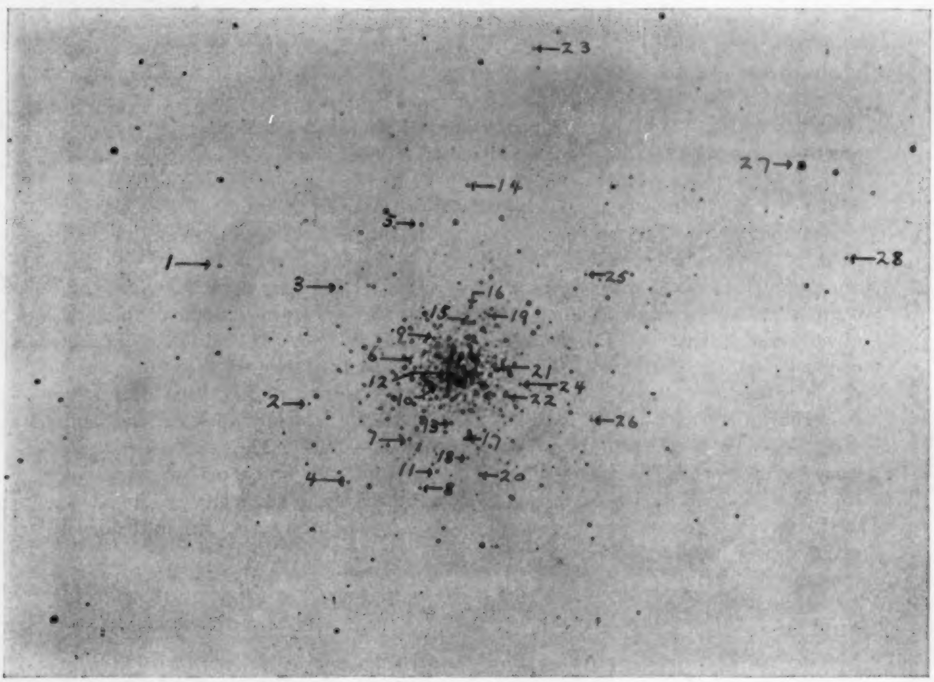
1. *Earlier results.*—The position of Messier 68 = N.G.C. 4590 for 1900 is:

Right ascension	$=12^{h}34^{m}.2$	Declination	$=-26^{\circ}12'$
Galactic longitude	$=268^{\circ}$	Galactic latitude	$=+36^{\circ}.6$

There are no early measures of magnitude for the individual stars, aside from roughly estimated limiting values by Bailey,[1] and no

North

West



THE VARIABLE STARS IN MESSIER 68

variable stars had been reported prior to our study. Holetschek's[2] integrated visual magnitude of the cluster is 8.2. The diameter estimated from the Franklin-Adams chart, $5'.3$, has led in *Mount Wilson Contribution* No. 152, to the parallax

$$\pi = 0''.000062, \tag{1}$$

[1] *Harvard Annals*, **60**, 212, 1908; **76**, 46, 1915.

[2] *Annalen der k.k. Universitäts Sternwarte in Wien*, **20**, 114, 1907.

to which corresponds the linear galactic co-ordinates, in units of 100 parsecs,

$$R = 161$$
$$R \cos \beta = 129$$
$$R \sin \beta = +97$$

2. *Mount Wilson photographs.*—The observations in Table I have all been made at the primary focus of the 60-inch reflector. The remarks in the last column show to what use the various plates have been put. Although the southern declination of this cluster greatly limits the working season with the 60-inch reflector and is also unfavorable to high accuracy in the comparison with polar standards, the plates are of good quality and the results appear to be trustworthy.

TABLE I

PHOTOGRAPHS OF MESSIER 68 (N.G.C. 4590)

Plate Number	Date G.M.T.	Kind of Plate	Exposure Time	Remarks
4501*......	1918, July 3.68	S 27	5^m, 5^m, 1^m	Variables
4842......	1919, Feb. 24.91	S 27	15	Variables
4843*......	1919, Feb. 24.92	S 27	1 1 1	Photographic magnitudes, variables
4844*......	1919, Feb. 24.93	Iso + C	5 5 5	
4845*......	1919, Feb. 24.95	S 27	1 1 1 1^m	
4855*......	1919, Feb. 25.92	Iso + C	5 1 5	Photo-visual magnitudes
4856*......	1919, Feb. 25.92	S 27	2 2 2	Photographic magnitudes, variables
4857*......	1919, Feb. 25.93	S 27	10 10 2	Variables
4858*......	1919, Feb. 25.94	Iso + C	15 15 2	Photo-visual magnitudes, variables
4859*......	1919, Feb. 25.95	S 27	1 1 1	Photographic magnitudes, variables
4863......	1919, Feb. 27.88	S 27	12	Variables, luminosity-curve
4864......	1919, Feb. 27.90	S 27	35	Variables, chart
4911......	1919, May 24.68	S 30	20	Variables
4924......	1919, May 25.670	S 30	50	Variables, positions, ellipticity, luminosity-curve
4935......	1919, May 26.68	S 30	20	Variables

* Plates with multiple exposures are polar comparisons.

3. *Variable stars.*—By comparing the various plates in a stereocomparator, Miss Ritchie has found that the 28 stars listed in Table II undergo appreciable variation in light. The x and y co-ordinates in the second and third columns give the intervals of right ascension and of declination from the center; x is positive east, and y is positive north of the cluster. The positions are believed to be sufficiently accurate for identification. On the accompanying reproduction of Plate 4864 the variable stars are indicated by arrowheads.

The magnitudes have been determined as usual through the intermediary of polar comparison plates and by the measurement of some twenty comparison stars on all photographs listed in Table II. The last column of the table shows the differences between the photo-visual magnitude on Plate 4858 and the mean of the photographic magnitudes on Plates 4857 and 4859; these values of the variable color-index apply, of course, only to one phase of the light variation of each star. The bluish color for all but No. 27 indicates that the variables are of the usual cluster type. The observed ranges of light-variation and the similarity of the median magnitudes also support this view, although neither range nor median brightness is definitively determined.

A comparison of the magnitudes for any variable in Table II with the corresponding dates of observation in Table I shows that probably all except No. 27 have periods of less than a day. It appears reasonable to assume that these 27 stars belong to one or more of the sub-types[1] of Cepheid variables whose absolute photographic median magnitudes are approximately -0.2 (*Mount Wilson Contribution* No. 151, p. 27).

The apparent photographic median magnitude cannot be derived with certainty for a given variable because of insufficient observations to determine the light-curve completely. The tabulated medians vary from 15.65 to 16.21; the average median is 15.90 ± 0.10 (average deviation). Considering that all observations refer to a typical star, however, we derive the following fairly reliable mean value for the 27 variables:

$$\text{Median} = 15^{\text{M}}.90 \pm 0.02 \text{ (p.e.)}. \qquad (2)$$

As a further check of this value, the median of the means for the ten brightest and for the fifteen faintest[2] magnitudes in Table II is

$$(16.42 + 15.33)/2 = 15^{\text{M}}.88.$$

[1] On the basis of the observed range and the relative number of bright and faint magnitudes, we infer that the variables numbered 4, 6, 8, 13, and 28 may belong to Bailey's sub-class *c*, for which the characteristics are very short period, small amplitude of variation, and light-curves practically symmetrical.

[2] For the average cluster-type star the duration of "brighter than median" is to the duration of "fainter than median" approximately as two to three.

TABLE II

POSITIONS AND OBSERVATIONS OF 28 NEW VARIABLE STARS IN MESSIER 68

Variable	Position		Magnitudes on Photographic Plates										Observed Range	Median Magnitude	Provisional Color-Index
	x	y	4842	4843	4856	4857	4859	4863	4864	4911	4924	4935			
1	−4′40″	+1′49″	15.99	....	16.03	15.88	....	15.43	15.28	15.65	15.66	15.52	0.75	15.66	+0.07:
2	−2 48	−0 45	16.39	....	16.24	16.02	16.11:	16.18	16.16	15.69	16.08	16.28	0.70	16.04	+0.34
3	−2 20	+1 31	16.34	....	15.96	15.79	16.09:	15.76	15.54	15.93	15.93	15.86	0.80	15.94	+0.46
4	−1 57	−2 11	15.93	....	16.02	15.79	15.77	15.84	15.65	15.98	15.56	16.01	0.46	15.79	+0.21
5	−0 56	+2 50	16.14	....	15.85	15.76	15.90	15.62	15.51	15.69	15.77	15.91	0.63	15.82	+0.21
6	−0 54	+0 17	15.90	15.74	16.00	15.64	15.71	15.73	15.77	15.65	15.93	16.03	0.39	15.84	+0.25
7	−0 50	−1 19	15.85	....	15.87	15.56	15.65	15.78	15.48	15.65	16.16	15.94	0.68	15.82	+0.26
8	−0 38	−2 14	16.12	....	16.03	15.79	16.00	15.84	15.82	15.69	16.14	15.74	0.45	15.92	+0.43
9	−0 31	+0 40	16.12	15.72	16.07	16.10	....	15.88	15.89	15.90	15.43	16.28	0.85	15.86	+0.40
10	−0 25	−0 16	16.62:	15.92	15.93	16.20	15.84	16.21	15.28:	16.15	16.20	15.60	0.61	15.90	+0.47
11	−0 18	−1 52	15.93	....	16.11	16.06	16.02	15.60	15.31	15.53	15.87	15.97	0.80	15.71	+0.33
12	−0 10	−0 1	16.23	15.70	15.75	15.64	15.07	15.56	16.08	16.01	15.85	16.14	1.16	15.65	+0.27
13	−0 6	−0 56	15.90	....	16.28	16.20	16.07	15.62	15.77	15.74	15.66	16.22	0.66	15.95	+0.24:
14	−0 4	+3 38	15.55	15.56	16.29	16.10	....	15.16	15.92	15.98	15.82	15.50	0.79	15.90	+0.29:
15	+0 9	+0 58	16.14	....	15.89	15.69	15.65	15.76	16.08	16.36	16.08	15.78	0.71	16.00	+0.21
16	+0 11	+1 20	16.12	15.90	15.89	15.74	15.71	15.73	15.95	16.43	16.16	15.86	0.72	16.07	+0.17
17	+0 16	−1 15	16.60:	....	15.76	15.95	15.65	15.78	16.16	16.56	16.04	16.39	0.91	16.10	+0.50
18	+0 19	−1 36	16.28	15.90	16.05	15.97	16.02	16.15	16.16	15.72	15.59	16.22	0.69	15.94	+0.29
19	+0 33	+1 10	16.21	15.94	15.89	15.74	15.74	15.82	15.98	15.65	16.11	15.84	0.56	15.93	+0.24
20	+0 34	−1 54	15.82	15.74	16.02	15.81	15.93	15.80	15.45	15.78	15.59	16.01	0.57	15.74	+0.45
21	+0 48	+0 8	16.60	15.92	16.05	16.20	16.00	15.82	16.19	16.26	16.16	16.35	0.78	16.21	+0.57
22	+1 1	−0 22	16.52	15.92	16.42	16.32	16.07	15.78	16.14	16.41	16.04	15.30	1.22	15.91	+0.46
23	+1 4	+6 20	16.34	....	16.00	15.88	....	15.76	15.85	15.78	15.08	16.16	1.26	15.71	+0.22
24	+1 14	−0 8	15.90	15.86	16.09	16.10	16.00	16.11	16.01	16.34	16.00	15.74	0.60	16.04	+0.26
25	+2 21	+2 3	15.93	15.77	16.07	16.10	....	16.21	16.19	15.90	16.00	15.99	0.44	15.99	+0.39
26	+2 38	−0 44	15.68	15.67	16.11	16.10	....	16.11	15.89	16.09	16.35	15.72	0.68	16.01	+0.39
27	+6 20	+4 23	....	11.62	....	....	11.36	10.88	....	14.89	15.04	14.94	4.0±	13.0±	+2.0±
28	+7 20	+2 40	15.93	15.74	16.14	16.04	....	15.67	15.62	16.04	15.66	15.97	0.52	15.88	+0.76
Means*													0.72	15.90	+0.34

* Excluding No. 27.

Arranging the color-indices of Table II in order of the corresponding photographic magnitudes, we make the following tabulation, showing the anticipated increase of color-index with decreasing brightness, which is typical of this kind of variation (cf. Figs. 3, 4, and 5 of *Mount Wilson Contribution* No. 154).

Mean Pg. Magnitude	Number of Variables	Mean Color-Index
15.61	5	$+0^{M}.23$
15.80	5	0.32
15.91	5	0.29
16.05	6	0.41
16.12	6	+0.41

4. *Relation of absolute magnitude to color-index.*—From the polar comparison plates the magnitudes have been determined both for a series of selected comparison stars, to be used in studying the variables, and for a complete list of all the brighter stars (outside the central nucleus but within $3'.5$ of the center), to be used in determining the parallax of the cluster and the upper limits of luminosity. Table III contains the positions, magnitudes, and colors of these stars. By accepting the value of the parallax adopted in a following section, the apparent photographic and photo-visual magnitudes may be transformed into absolute values by subtracting 16.15 from the magnitudes given in Table III. It is then seen that these stars are all giants, most of them red and yellow, but a few of the fainter ones blue.

The interdependence of color and magnitude among the giant stars is illustrated by Table IV and Fig. 1. The usual color law for giant stars in clusters, already found in several systems,[1] holds also in this case; that is, the fainter the giant, the bluer is the color, and, if the star is a Cepheid variable, the shorter is its period. The last group of Table IV (not plotted in Fig. 1) contains 27 variables; the next to the last group contains 3 stars, and the preceding groups contain 5 stars each. The variables agree perfectly with invariable stars in the relation of median color to absolute luminosity.

[1] *Mt. Wilson Communications*, No. 34, 1916.

TABLE III

MAGNITUDES AND COLORS OF 56 STARS IN MESSIER 68

Star	Position x	Position y	Magnitude Photographic	Magnitude Photovisual	Color-Index	Star	Position x	Position y	Magnitude Photographic	Magnitude Photovisual	Color-Index
101†	−7′ 25″	−5′ 9″	12.06	11.06	+1.00	129*†	+0′ 15″	+0′ 58″	15.07	14.16	+0.91
102†	−2 48	−1 53	15.97	15.53	+0.44	130*	+0 16	+0 43	14.85	13.98	+0.87
103	−2 39	−1 32	15.33	14.60	+0.73	131*	+0 18	−1 10	14.92	14.02	+0.90
104*	−2 39	−0 35	14.35	13.12	+1.23	132*	+0 22	+0 19	14.32	12.93	+1.39
105*	−2 26	−0 57	15.06	14.16	+0.90	133*	+0 26	+0 54	14.76	13.80	+0.96
106†	−2 16	−0 4	15.92	15.20	+0.72	134†	+0 28	−1 24	16.01	15.30	+0.71
107	−2 8	−2 2	15.60	14.56	+1.04	135*	+0 32	+2 24	15.02	14.18	+0.84
108†	−2 3	+0 2	16.18	>16.0	<+0.2	136†	+0 36	+4 19	15.80	15.15	+0.65
109†	−2 2	+2 36	15.92	15.34	+0.58	137*	+0 39	+3 2	15.06	14.41	+0.65
110*	−1 49	+0 24	14.75	13.69	+1.06	138†	+0 54	+0 42	15.62	14.58	+1.04
111	−1 46	−0 20	15.84	15.11	+0.73	139*	+0 58	+0 8	14.81	13.98	+0.83
112†	−1 41	+1 37	15.44	14.53	+0.91	140	+1 2	+2 24	15.58	14.99	+0.59
113	−1 34	+3 2	13.98	12.42	+1.56	141*	+1 2	+0 3	14.45	13.29	+1.16
114	−1 34	−2 15	14.00	12.46	+1.54	142	+1 8	−1 13	15.67	15.36	+0.31
115†	−1 9	−0 33	13.86	12.38	+1.48	143*	+1 9	−0 34	15.02	14.34	+0.68
116†	−1 6	+0 57	15.74	14.97	+0.77	144*	+1 14	−2 19	14.99	14.11	+0.88
117*	−1 3	+0 4	15.07	14.26	+0.81	145*	+1 17	+1 26	14.31	12.88	+1.43
118	−0 40	−1 28	15.40	14.39	+1.01	146*	+1 24	+0.52	14.60	13.26	+1.34
119	−0 40	+1 7	13.99	12.40	+1.59	147	+1 27	+1 16	14.08	12.66	+1.42
120*	−0 37	−0 57	15.08	13.98	+1.10	148†	+1 52	−1 18	15.82	15.32	+0.50
121	−0 26	+0 20	15.66	15.32	+0.34	149	+2 9	+0 10	15.80	15.66	+0.14
122*†	−0 14	+2 53	14.63	13.56	+1.07	150†	+2 9	+1 45	15.74	14.97	+0.77
123*	−0 13	+0 40	15.02	14.20	+0.82	151*	+2 13	−0 37	15.02	14.15	+0.87
124*	−0 10	−0 15	14.67	13.70	+0.97	152†	+2 26	−1 21	16.40	15.32	+1.08
125*	−0 10	−3 12	14.64	13.44	+1.20	153†	+2 36	+1 57	15.20	15.56	+0.64
126	−0 8	+0 32	15.41	14.54	+0.87	154†	+2 38	+0 42	15.82	15.61	+0.21
127†	−0 7	+1 44	16.32	15.48	+0.84	155*	+2 47	+1 38	14.67	14.20	+0.47
128*	+0 6	−0 10	14.79	13.67	+1.12	156†	+8 26	+4 50	12.87	11.78	+1.09

* Bright stars used for the determination of distance.

† Comparison stars used for the study of variables.

5. *The distance of Messier 68.*—As described in *Mount Wilson Contribution* No. 151, Section 5, the mean apparent photographic magnitude of the bright stars can be used as a measure of distance.

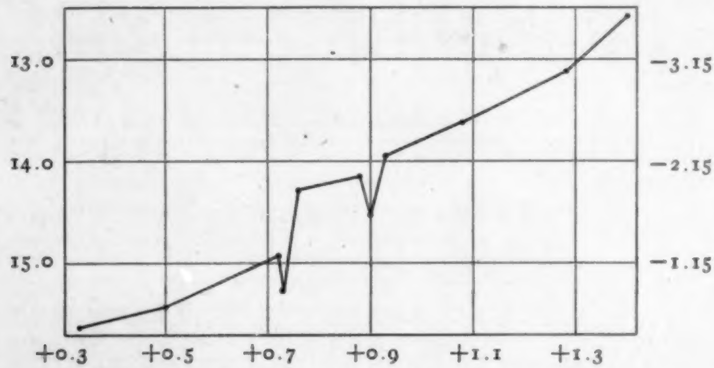


FIG. 1.—The color of giant stars in Messier 68. Abscissae are mean color indices; ordinates are apparent and absolute magnitudes.

Excluding the five brightest stars, we obtain from Table III for the next twenty-five stars in order of brightness the mean value of 14.80 ± 0.21 (average deviation) with extremes of $14^{\mathrm{M}}.31$ and $15^{\mathrm{M}}.08$.[1]

TABLE IV

COLOR OF GIANT STARS

Mean Photo-visual Magnitude		Mean Color-Index
Apparent	Absolute	
12.59	−3.56	$+1^{\mathrm{M}}.40$
13.12	−3.03	+1.28
13.61	−2.54	+1.08
13.95	−2.20	+0.93
14.15	−2.00	+0.88
14.28	−1.87	+0.76
14.52	−1.63	+0.90
14.93	−1.27	+0.72
15.26	−0.89	+0.73
15.41	−0.74	+0.50
15.61	−0.54	+0.33
15.57	−0.58	+0.34

If, as previously adopted, this mean value corresponds to absolute magnitude -1.5, we derive as the parallax of the cluster

$$\pi = 0''.000055. \qquad (3)$$

[1] Cf. Table II of *Mt. Wilson Contr.* No. 152, 1917.

A better determination of the distance may be based on the variable stars, whose intrinsic luminosity is known with higher accuracy than that of the brighter stars. Accepting -0.23 as the absolute value of the median photographic magnitude,[1] we compute from the observed value (2)

$$\pi = 0''.0000595. \tag{4}$$

These new determinations are of much higher weight than (1), which is based on the measured diameter alone. Assigning weights 1, 2, and 4 to (1), (3), and (4), respectively, we derive the definitive value

$$\pi = 0''.000059,$$

which differs from the earlier determination by less than 5 per cent. Corresponding to the adopted parallax, we have, in units of 100 parsecs,

$$\begin{aligned} R &= 170 \\ R\cos\beta &= 137 \\ R\sin\beta &= +102 \end{aligned}$$

and, to reduce from apparent to absolute magnitude, we compute the factor $m-M=16.15$.

The difference Median *minus* "Mean of 25 Brightest," $+1.10$, is somewhat small; but it differs by less than the adopted probable error from the mean value (derived from several clusters in *Contribution* 151) that was used in *Contribution* 152 for the determination of the distance of a considerable number of clusters in which variable stars are infrequent or unknown.

6. *The general luminosity-curve.*—The relation of the frequency of stars to absolute brightness is tabulated for two photographs in Table V. Numbers in parentheses show the frequencies when the known variable stars are excluded. On the plate of longer exposure, No. 4924, the magnitudes have been determined for more than 800 stars in representative selected areas that cover about one-fourth of the whole cluster; on Plate 4863 all stars in the cluster brighter than magnitude 17.5 were measured, excepting those within half a minute of arc of the center. Because of the

[1] *Mt. Wilson Contr.* No. 151, p. 27, 1917.

small apparent diameter and the fairly high galactic latitude of Messier 68, no correction for background stars has been considered necessary. The reduction of the measures has involved, however, the usual correction for irregularities of the measuring scale and for distance from the center of the plate, and also for the unlike magnitude intervals in Table V.

TABLE V

LUMINOSITY AND FREQUENCY OF STARS

Plate 4863		Plate 4924	
Absolute Pg. Mag.	Number of Stars	Absolute Pg. Mag.	Number of Stars
−2.2	2.7	−2.4	0.7
−1.76	4.3	−2.06	1.4
−1.38	5	−1.64	1.4
−1.01	9	−1.25	3
−0.68	24 (23)	−0.86	6 (5)
−0.46	61 (55)	−0.56	11 (10)
−0.28	72 (65)	−0.28	14 (12)
−0.11	60 (53)	0.00	14 (12)
+0.11	31 (29)	+0.27	11 (10)
+0.4	24 (22)	+0.55	9
+0.7	25	+0.83	13
+1.0	41	+1.1	17
+1.3	70	+1.4	19
		+1.7	25
		+1.9	42
		+2.2	74
		+2.5	130
		+2.7	234

The relatively high frequency of stars near the median magnitude, Fig. 2, appears to be much the same in this cluster as in five other globular clusters previously studied.[1] With the variable stars omitted, the phenomenon of a secondary maximum is still distinctly shown. From these results it appears that the general luminosity-curve in a star cluster cannot be accepted as a symmetrical probability-curve. The computation by Schouten[2] and Coeberg[3] of the distance of clusters, on the basis of the relative frequency of stars of the brightest few magnitudes, is therefore

[1] *Mt. Wilson Contr.* No. 155, 1917.

[2] *Verslagen Koninklijke Akademie van Wetenschappen te Amsterdam,* 20, 1147, 1293, 1918.

[3] *Hemel en Dampkring,* November 1918.

open to serious objection because they assume the luminosities to be distributed according to a normal error-curve. The questionable assumption is obviously responsible for the anomalous results obtained by them for the absolute magnitudes of all stars in clusters.

7. *The maximum luminosity in Messier 68.*—The mean absolute magnitude of the five brightest cluster stars is -2.16 photographic, and -3.55 photovisual. Variable No. 27 is excluded from this group as possibly not a member of the cluster; if a cluster star, its absolute photographic magnitude at maximum would be of the order of -5.0. The brightest blue star in the cluster appears to be No. 20 with the absolute photo-visual magnitude -0.5.

In Messier 68 there are about 250 stars brighter than the absolute magnitude zero; in Messier 13 and

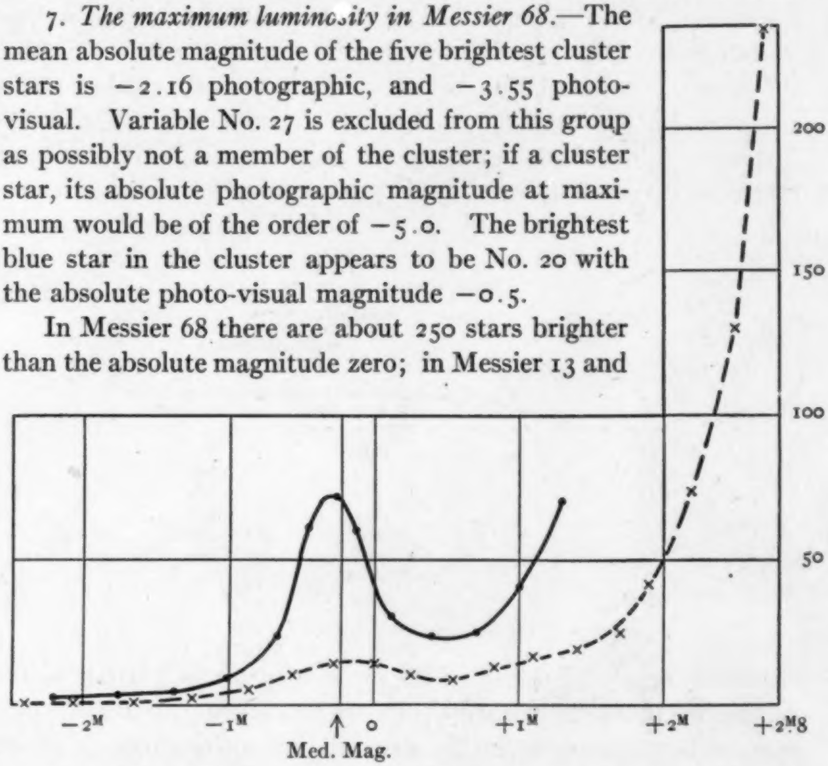


FIG. 2.—General luminosity-curves for Messier 68, from Plates 4863 (full line) and 4924; abscissae are absolute photographic magnitudes; ordinates, numbers of stars.

Messier 3 there are something like twice as many stars brighter than the same limit of absolute brightness.

8. *The form of the cluster.*—Using the system of superposed sectors and rings, described in earlier discussions of the ellipticity of clusters, we have counted 1700 stars brighter than absolute magnitude $+2.7$ on Plate 4924. There is no appreciable deviation from perfect circularity. The results appear in Table VI, where opposite 30° sectors are combined to eliminate error in centering.

9. *Summary and conclusions.*—A. The results of a characteristic photometric study of Messier 68, a hitherto unexplored southern globular cluster, include the following items: (1) discovery of 28 variable stars, all but one of which appear to be typical cluster variables; (2) verification of the earlier result that cluster-type variables are characteristically bluer at maximum light than at minimum; (3) tabulation of the magnitudes and colors of the brightest giant stars of the cluster; (4) a new determination of the distance (55,000 light-years), based on diameter, variables, and bright stars, which differs very little from an earlier value based on diameter alone; (5) proof of the circularity of the cluster, so far as the two thousand brightest stars are concerned; (6) discovery of a secondary maximum in the general luminosity-curve at about the median magnitude of the short-period variable stars; (7) evidence that this cluster, which is less concentrated to the center than usual, is much poorer in giant stars than some other globular systems.

TABLE VI

DISTRIBUTION OF STARS

Position Angle	Number of Stars	
	Distance from Center 0.5 to 5.0 mm	Distance from Center 1.0 to 4.0 mm
15°	293	205
45	279	207
75	284	212
105	277	209
135	280	208
165	288	209
Mean	284	208

B. The following general conclusions, resulting from previous studies of clusters, are directly supported by the evidence from Messier 68: (1) The general luminosity-curve for the stars in a cluster differs so widely from a symmetrical probability-curve that the former is of little value in determining the distance of clusters by the method tentatively suggested by Kapteyn (cf. Fig. 2). (2) The median brightness of the short-period variables in any

globular cluster appears to be an astrophysical constant whose value is a little more than one magnitude fainter than the mean of the magnitudes of the 25 brightest stars in the cluster; this result gives weight to the distances of clusters derived from measures of their brightest stars. (3) The diameter of the image of a globular cluster on a photographic chart is a valuable criterion of distance. (4) The brightest giant stars in globular clusters are always very red and have absolute photo-visual magnitudes between -4 and -3. (5) With decreasing brightness, at least as far as absolute-magnitude zero, the average color-index of the giant stars decreases (cf. Fig. 1).

Mount Wilson Observatory
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Minor Contributions and Notes

THE PROBLEM OF THE δ CEPHEI VARIABLES

ABSTRACT

δ Cephei variables. The author has recently suggested a *binary* theory which postulates that the variability of these stars is due to the action of satellites. If this is correct, we should expect to find variables of this type which undergo only slight variations of brilliancy as well as some which vary a full magnitude. The reason such variables have not been recognized may be that their properties do not facilitate discovery as much as the properties characteristic of known δ Cephei variables. It is suggested that a careful study of eighteen stars recently listed by Adams and Joy might help to decide between the binary and pulsation theories of these variables.

In the *Publications of the Astronomical Society of the Pacific* (**31**, 184, 1919), a list of eighteen stars is given that have remarkable properties in common. According to Adams and Joy their spectral types all lie between F and K, their angular proper motions are less than $0\overset{''}{.}040$, except one which is $0\overset{''}{.}100$; they are all within galactic latitude $\pm 26°$, except two at $+32°$ and $-43°$; their absolute magnitudes, as indicated by spectroscopic determination, range from -1 to -4.

1. The partial resemblance with the δ Cephei type is striking; still the stars are not classified as belonging to that type, because a number of other qualities, supposed to be characteristic, have not yet been found. Only six of the stars have so far shown any variable velocity and no orbits have been computed. Furthermore no variation of light or of spectral type is observed, except that one star is suspected of variability.

Hitherto it was supposed that δ Cephei stars had a light-range of at least half a magnitude, with a corresponding range of spectral type, and that the variable velocities, when computed on Doppler's principle, indicated a number of orbital peculiarities, such as small mass of the satellite, large eccentricity, and the periastron situated on the far side of the line of nodes.

2. Now it is suggested that these properties are not characteristic of the δ Cephei class and that they only facilitate discovery.

The writer has tried to show this in an article which appeared under the title "Das Blinksternproblem."[1] The explanation starts from the binary theory and is based on the one very simple hypothesis, that the near approach of a satellite is capable of producing an eruption of light on the visible star, somewhat like the action of the sun on a comet.

The hypothesis entails a number of natural consequences: the luminous eruption is the stronger the nearer the approach of the satellite; it lags behind the passage through periastron; the decline of light will be slower than its eruption; the side of the variable star which turns toward the satellite is continually brighter than the opposite side.

3. This hypothesis being admitted, the properties mentioned in paragraph 1 are the very ones that facilitate discovery in that they are apt to increase the range of apparent light-variation.

a) Evidently the visible light-range is greatest when the angle i between the orbit and the tangent plane to the celestial sphere is nearly a right angle. The product $m \sin i$, in which m is the mass of the satellite, is always found to be a small number. Hence discovery is favored if the smallness of the product is not due to i but to m. This will account for the fact that the spectrum of the satellite does not show and that transits over the disks of the bright stars are not observed.

Another question is, Why should the product $m \sin i$, and consequently m, be always a small quantity? It is quite likely that a large satellite might distort the characteristic light-curve of the δ Cephei stars and make its recognition difficult. Could not some variables that are classified among the eclipsing or β Lyrae stars be in reality of the δ Cephei type?

b) That large eccentricities increase the range of light-variation and thus facilitate discovery needs no further comment.

c) The peculiar situation of the periastron beyond the line of nodes is no longer a puzzle because the eruption of light is best seen

[1] *Astronomische Nachrichten*, 209, 33, 1919.

when the satellite passes through periastron between the observer and the star.

4. The conclusion is that there may be δ Cephei variables which have satellites of greater mass but which have not been recognized as such. Again there may be others which, on account of small orbital eccentricity, undergo only slight variation of brilliancy, and finally there may be such as vary to a full magnitude on the side turned away from the observer, periastron lying on our side of the nodes.

From this point of view the eighteen stars listed by Adams and Joy deserve the greatest attention and should be followed with photo-electric photometers and with spectrographs of high dispersion, in order to obtain light-curves and velocity-curves for intercomparison. The burning question between the binary and the pulsation theory of the δ Cephei variables might then be brought nearer to a final solution.

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December 25, 1919